PRACTICAL EXERCISES IN MAGNETISM AND ELECTRICITY

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PRACTICAL EXERCISES

MAGNETISM & ELECTRICITY

BEING A LABORATORY COURSE FOR SCHOOLS OF SCIENCE

BY

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PREFACE

THE following practical exercises in Magnetism and Electricity are designed primarily to meet the wants of pupils of Schools of Science in connection with the Board of Education, where this subject is selected for detailed study during the third and fourth year's work in Physics in an organised course of science.

The book at the same time does more than this: it is suitable for students preparing for the ordinary elementary examination of the Board of Education in Magnetism and Electricity, in Technical Schools and Evening Science Classes where individual practical work is possible. The experiments are of a kind which candidates presenting themselves in this subject at the Matriculation and Intermediate Science Examinations of the London University, or at the examinations for secondary school pupils, held by the Universities of Oxford and Cambridge, the College of Preceptors, the London Technical Education Board, and other bodies, might with advantage perform themselves.

It is as well to point out, however, that though suitable for all the examinations mentioned, the book follows no single syllabus; the order of the subjects represents what my own experience indicates as the best means of giving students systematic and logical ideas.

In writing all sections, the needs of technical students who intend later to take up some branch of electrical engineering

have been kept in mind, and, where possible, the bearing of the general principles elucidated upon the practical applications of the science with which the engineer is more directly concerned have been indicated. It will be noticed that the range of work included in the last part (Voltaic) of the book is much more extensive than in the previous sections. This is intentionally arranged, since this portion of the subject has a more direct application to technical work.

Students frequently find difficulty in understanding the theory of an experiment in which they may be engaged. For this reason each experiment is preceded, where deemed necessary, by a brief statement of the theory upon which the experiment is based.

In nearly every case the conditions of the experiments are reduced to their lowest terms, with a view to train the student not to rely upon elaborate apparatus for proving the fundamental facts of the science. The illustrations, too, have been designed to make the object and method of the experiments as plain as possible.

The Additional Exercises at the end of various chapters are selected so as to serve not only as examples on the work of the previous chapter, but also as suggestions towards further practical exercises for the use of students who have already carried out most of the experiments described in the text. Those followed by a date are from examination papers of the Board of Education.

I am glad to express my grateful acknowledgments to Professor R. A. Gregory and to Mr. A. T. Simmons, B.Sc., for their kindly and experienced criticism throughout the preparation of the manuscript and the passage of the book through the press.

H. E. H.

September 1901.

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PART I.

CHAPTER I

PRELIMINARY EXPERIMENTS IN MAGNETISM

1. Properties of Magnets

Apparatus required.—Lodestone and bar-magnet. Iron filings. Sewing-needle (or piece of watch-spring). Suspension for lodestone (see note 1, p. 216).

(i.) **The Lodestone** (Fig. 1).—(*a*) Dip the lodestone into iron filings. Sketch as accurately as you can the general appearance of the effect.

*(*b*) Suspend the lodestone so that it swings freely in a horizontal plane. Notice the manner in which it swings to and fro, and finally comes to rest pointing in a definite direction. Mark the points on the bench towards which the lodestone is pointing; also mark, by means of gummed paper, that end of the lodestone which points towards the north.

FIG. 1.—A lodestone which has been dipped into iron filings.

(ii.) **A Bar-magnet.**—Repeat Expt. i. (*a*) and (*b*), using

a bar-magnet instead of the lodestone, and observe how closely the magnet resembles the lodestone in its magnetic properties.

(iii.) ***An Unmagnetised Sewing-needle.***—*Repeat the same* experiments with an unmagnetised sewing-needle (or, piece of watch-spring), and notice how it fails to exhibit the characteristic properties of the lodestone.

The next experiments will indicate how the properties of the lodestone may be transmitted to the needle or watch-spring.

2. Methods of Magnetisation

Apparatus required.—Three needles. Two pairs of small bar-magnets. Spiral (10 cms. long, 0.5 cm. wide) of cotton-covered copper wire wound on a straight piece of glass tubing. Voltaic cells (either two large Bunsen cells, or a secondary cell).

(i.) **Method of Single Touch.**—Lay a needle on the table, and hold it firmly by pressing a finger on the eye of the needle; or, better still, fix it to the table by soft wax at the ends (see note 2, p. 216); rub the marked pole of the lodestone along the needle from eye to point; lift the lodestone some distance away from the table, and bring it down again on to the eye of the needle, and repeat this operation several times (Fig. 2, i.). Apply the previous tests and satisfy yourself that the needle now has the same properties as the lodestone.

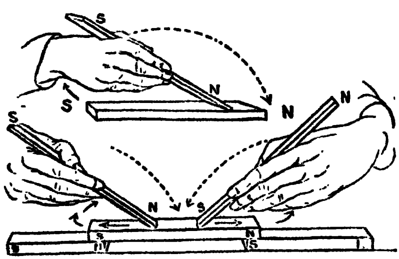


FIG. 2 (i. and ii.).—Methods of magnetising steel.

(ii.) **Method of Divided Touch.**—Fix a needle on the table as in Expt. 2 (i.); place the opposite poles of two bar-magnets close together in contact with the middle of the clock-spring, then draw them apart towards opposite ends of the spring. Lift them away, and bring them together again at the centre, and repeat this several times.

A stronger degree of magnetisation is obtained if the spring is supported at its ends on the poles of two other bar-magnets, in each case the poles being of the same polarity as that of the movable magnets above it (Fig. 2, ii.).

(iii.) **By means of an Electric Current.**—Insert a needle into the spiral of copper wire (Fig. 3), and pass a strong electric current through the wire for a few seconds. After stopping the current, remove the needle, and test it for magnetisation.

FIG. 3.—A spiral of cotton-covered wire round a glass tube.

Magnetic Attraction and Repulsion

Apparatus required.—Two needles (one magnetised as in Expt. 2 (i.), and one unmagnetised). Lodestone. Suspension.

(i.) Suspend the magnetised needle, and observe which end points towards the north (this end is called the *north-seeking pole*). Hold near to this pole the unmarked end of the lodestone, and note the *attraction*. Hold the same end of the lodestone near to the south-seeking pole of the needle, and note the *repulsion*. Repeat these observations, but use the *marked* end of lodestone, and in this manner verify the following rules:—

Unlike Poles Attract.
Like Poles Repel.

(ii.) Repeat Expt. 3 (i.), using the unmagnetised needle. Note how *attraction* takes place in all cases.

Carefully remember, therefore, that *repulsion is the only sure proof that the needle is magnetised.*

Magnetic and Non-magnetic Substances

Apparatus required.—Fragments of nickel and cobalt. Bar-magnet. Short lengths of zinc, wood, copper, glass, etc. Suspension (Fig. 4).

So far only iron or steel have been experimented with, and the results indicate that these may be termed *magnetic substances.* It will be found in the following experiments that other substances are also magnetic.

(i.) **Magnetic.**—Bring a bar-magnet (or lodestone) in contact with some fragments of *nickel* and of *cobalt;* both are attracted, consequently these also *are* magnetic substances.

(ii.) **Non-magnetic.**—Suspend short lengths of *zinc* rod, *wood*, *copper*, *tin*, and of *glass.* Notice none of these are

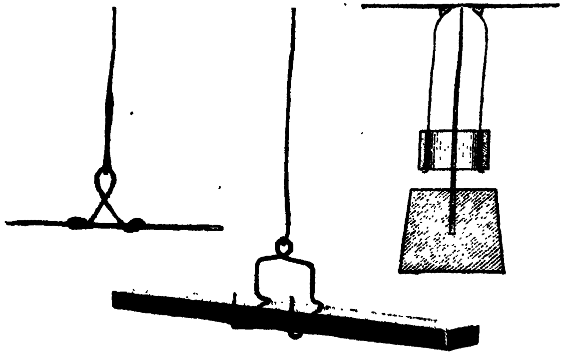


FIG. 4.—Methods of suspending magnets.

affected by a magnet, and consequently *are not* magnetic substances.

5) Transmission of Magnetic Effects through various Solids

Apparatus required.—Suspended magnetised needle. Bar-magnet. Sheets of paper, zinc, wood, glass, etc.

(i.) Suspend a magnetised needle, and bring the pole of a magnet near to it; hold successively in front of the pole a sheet of copper foil, of zinc foil, of paper, or of wood. In no case is the deflection of the needle affected.

6) Destruction of Magnetism

Apparatus required.—Bar-magnet. French wire nail. Sus-

pended magnetised needle (or, compass-needle). Soft steel wire, bent twice at right angles. Magnetised needle. Bunsen burner. Metal tongs. Watch-spring.

(i.) **By Rough Usage.**—The effect is far more evident when a piece of fairly soft iron is used rather than steel; for example, a French wire nail about 7 cms. long is suitable for the purpose. Magnetise the nail by single touch, and test its magnetisation by bringing it near to a compass-needle. Strike it several times with a hammer, and test again; it will be found to have lost a considerable portion of its magnetism.

(ii.) **By Twisting or Distortion.**—Cut off a length of stout soft steel wire about 14 cms. long, and bend the ends at right angles to the wire, thus: ; this will enable the wire to be readily twisted by hand. Magnetise the straight portion of the wire by the method of single touch; test its magnetisation by bringing it near to a compass-needle. Twist the wire to and fro several times, and observe that it has lost all, or nearly all, its magnetism.

(iii.) **By Heat.**—Hold a magnetised needle in a Bunsen flame by means of metal tongs, or by wrapping the ends of a short length of copper wire round the needle; when red hot remove it, and allow to cool; test for magnetisation by means of a compass-needle.

7. Result of breaking a Magnet

Apparatus required.—Bar-magnet, watch-spring, and compass-needle.

(i.) Magnetise a piece of watch-spring, and break it into two pieces. Test each piece separately, and notice that each is a complete magnet in itself, having opposite poles at opposite ends. Notice that the broken ends have opposite polarity. Break one of the pieces again into two parts, and verify that each of the fragments is still a complete magnet. Treat one of the fragments in the same manner, if possible.

8. Loss of Magnetism by Soft Iron

Apparatus required.—Bar of *soft* iron. Bar-magnet. Compass-needle.

(i.) Endeavour to magnetise the soft iron bar by the method of single touch. Observe, by its action on a compass-needle, that it has derived scarcely any permanent magnetism.

9. Consequent Poles

Apparatus required.—Long steel knitting-needle. Bar-magnet. Compass-needle.

(i.) Magnetise the knitting-needle in four separate parts by the method of single touch, and so that a north-seeking pole is found at both ends; another north-seeking pole is also found at the centre, and south-seeking poles at one-quarter of the whole length from each end. Make a diagram of the knitting-needle and mark, by means of the symbols N and S, the locality of the consequent poles.

Additional Exercises

Magnetise two sewing-needles and float them vertically in a dish of water by means of two pieces of cork. Observe, and explain, the effect when they are floating near together. Reverse one of the needles in its cork, and again explain the effect observed.

2. Magnetise a long piece of clock-spring. State how you would treat the spring, without demagnetising it, so that, when held near to a compass-needle, it would exert no attraction or repulsion on the poles of the needle. Try the experiment.

3. Magnetise a knitting-needle so that it has consequent poles at the centre. If freely suspended so as to swing horizontally, how would you expect it to behave? Try this. If the needle is now broken into two equal parts, would either portion, when suspended, behave in the same way as the original needle? Try this.

4. Magnetise the given steel rod so that both ends are north-seeking. Map the magnetic field in the neighbourhood of the magnetised steel by means of iron filings. (Inter. County Sch., L.C.C. 1900.)

5. Magnetise one of the two similar pieces of steel by means of a pair of bar-magnets, and the other by means of an electric

current. In each case arrange that the marked end is north-seeking. Place the two magnets thus made with their axes in the same straight line, and with their marked ends adjacent, but at a short distance apart. Map the magnet field near the magnets by means of iron filings, and state, with reason, whether the magnets are of equal pole strength or not. (Inter. County Sch., L.C.C. 1900.)

6. A horse-shoe magnet lies flat on a sheet of brass which is supported by strings in such a way that it turns about a vertical axis but always remains horizontal. How will it place itself? (1893.)

CHAPTER II

MAGNETIC INDUCTION

Temporary Magnetism in Soft Iron

Apparatus required.—Pair of bar-magnets. Clamps. Small wire nails. Small strips of galvanised iron (see note 3, p. 216). Iron filings. Compass-needle. Suspension.

(i.) **Preliminary Observation.**—Dip a bar-magnet into a heap of small wire nails (or, better still, fragments of thin galvanised iron). The fragments are picked up readily, just as though they were permanent magnets and the result due to the attraction of unlike poles.

Are the fragments even *temporarily* magnetised?

(ii.) **Polarity of Distant End.**—Clamp a bar-magnet vertically, and immediately below it clamp a strip (12 or 14 cms. long) of galvanised iron. Test the *lower* end with filings, also with the compass-needle. Note how its polarity is the *same* as that of the *near* end of the bar-magnet. (The upper end cannot be tested in the same way, owing to the nearness of the bar-magnet.)

(iii.) **Polarity of Near End.**—Suspend the strip horizontally, and support a bar-magnet horizontally near to it (with the north-seeking pole near) Fig. 5. Bring the south-seeking pole of a second bar-magnet near to *a*, and at right angles to the strip. Note the *repulsion*, proving that *a* has *south-seeking* polarity. Reverse NS, and prove that *a* now has *north-seeking* polarity.

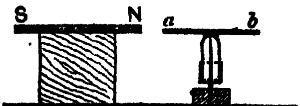


FIG. 5.—To explain Expt. 10 (iii.).

Take NS away, and again test the strip. It is now no longer a magnet.

This phenomenon of *temporary* magnetisation is termed *Magnetic Induction.*

The same phenomenon explains how a bar-magnet is capable of picking up iron filings, each filing being temporarily magnetised by the bar-magnet.

1 Magnetism induced in Soft Iron by a Temporary Magnet

Apparatus required.— Pair of bar-magnets. Clamps. Strips of galvanised iron. Short wire nails. Compass-needle. Two sewing-needles.

(i.) **Preliminary Observation.**—Clamp a large bar-magnet in a vertical position, with its north-seeking pole downwards, and hang from it a strip of galvanised iron. Bring into contact with the iron a number of small wire nails, and notice how long a chain of nails can be supported. The iron and each nail are temporarily magnetised. Test the polarity of the extreme end of the chain by means of a compass-needle.

(ii.) **Two Bar-magnets in Opposition.**—Bring near to the end N the south-seeking pole of a second bar-magnet. This second magnet will also act inductively on the iron and nails, but the induced polarity will be opposite to that already present. The magnetisation of the iron and nails is consequently weakened, and most of the nails fall off.

(iii.) **Two Bar-magnets in Conjunction.**—Replace everything as in Expt. 11 (i.). Now place the south-seeking pole of a second bar-magnet just below the end of the chain of nails. We can now add two or three more nails; the induction due to the south-seeking pole tends to strengthen that originally present, and consequently the induced magnetism is increased. Remove the south-seeking pole, several nails will fall off; if the north-seeking pole of the second magnet be now placed close to the end of the chain, more nails will fall off.

(iv.) **Mutual Action of Temporary Magnets.**—Suspend from the pole of a vertically-clamped magnet a bunch of sewing-needles, or three or four strips of galvanised iron.

Notice that the lower ends of all the needles have similar polarity, and mutually repel each other—the needles consequently bunch outwards.

12. Induced Magnetism may be created in a Permanent Magnet

Apparatus required.—Long steel knitting-needle (feebly magnetised). Bar-magnet.

(i.) Feebly magnetise a long knitting-needle, and suspend it in a stirrup. Hold the pole of a strong bar-magnet some distance away, and observe the repulsion between similar poles. Rapidly bring the magnet to within an inch of the repelled end of the needle, when *the original repulsion is converted into a strong attraction.*

13. Coercive Power

Apparatus required.—Bar-magnet. Clamp. Strip of galvanised iron. Short wire nails. Steel pen nibs.

(i.) **Soft Iron.**—Clamp a bar-magnet vertically. Suspend from its lower pole a strip of galvanised iron, and attach to the lower end of the strip as many wire nails as possible. Very carefully take hold of the strip and slide it off the end of the magnet; note whether the nails remain attached to it.

(ii.) **Steel.**—Repeat Expt. 13 (i.), but use steel pen nibs instead of soft iron. Carefully slide off the upper nib, and note whether the lower nibs fall off.

Soft iron readily "forgets" the magnetic treatment to which it has been subjected, and we say that it has very small *Coercive Power.* The reverse is the case with steel.

14. Susceptibility

Apparatus required. — Suspended magnetised needle. Pieces of unmagnetised steel and soft iron (of exactly the same shape and size).

(i.) Suspend a magnetised needle just above the level of the table, and place a bar of *unmagnetised* steel horizontally with

its end near to the north-seeking pole of the needle, and its length perpendicular to the needle's axis.

Now, place the soft iron (of similar size to the steel) on the opposite side of the needle, and alter its distance from the pole until the needle again points to the north (Fig. 6). The soft iron completely neutralises the effect of the steel, although it is much farther away from the needle than the steel is.

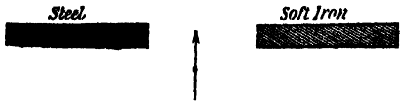


FIG. 6.—Expt. 14 (i.).

ADDITIONAL EXERCISE

1. A compass-needle and a straight strip of soft iron of the same length as the needle, are fastened together, so as to be in contact with each other at both ends. Will the force which tends to make the combination point north and south be the same as that which would act on the compass-needle alone? (1887.)

CHAPTER III

THE TANGENT LAW

15. Relation between Angle of Deflection and the Deflecting Force

Apparatus required.—Suspended magnetised needle. Bar-magnet. Drawing-board, fitted up with sheet of paper, etc. (see Fig. 8). Nest of weights. Metre scale.

(i.) **Magnetic Effects depend upon Distance.**—Suspend a magnetised needle (*ns*) so that it is swinging in a horizontal plane just above the surface of the bench; mark its position of rest. Place a bar-magnet (NS) near to the needle and in the position shown (Fig. 7). Notice how the needle is deflected into a position such as *n's'* by the force of attraction exerted by the pole N. The angle *sos'* is the *angle of deflection.* Vary the deflecting force by moving NS nearer to or farther from the needle, and notice how the angle of deflection is modified.

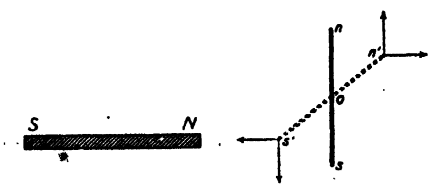


FIG. 7.—Expt. 15 (i.).

Is there any simple relation between the deflecting force and the angle of deflection? An experiment in which the deflecting force is due to gravitation affords the simplest method of obtaining information on this point.

(ii.) **The Tangent Law.**—Fasten a sheet of white paper on a drawing-board which is clamped in a vertical position. Fix a

small nail at the point O (Fig. 8). Suspend from O a string carrying a scale pan (of known weight, p). Fix an aluminium pulley-wheel at P, and pass over the wheel a second string, looped at Q, and carrying a scale pan (weight p') at the other end.

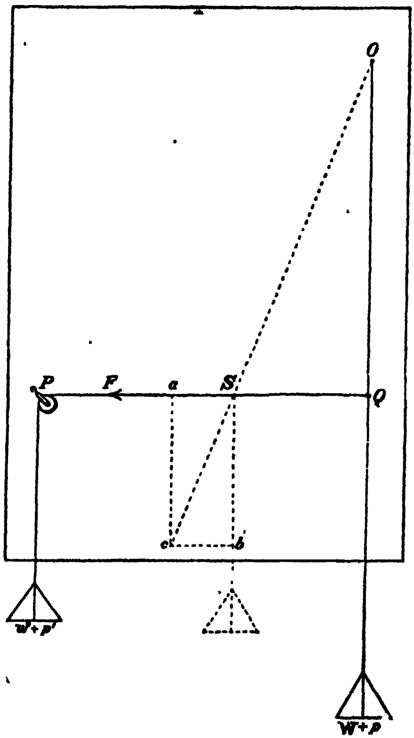


FIG. 8.—Expt. 15 (ii.).

Place a weight W in the pan p, so that the total weight is 20 grams. Adjust the string PQ so that it is quite horizontal, and draw the line PQ in pencil by means of a straight-edge. Measure the length OQ. Place a weight w in the pan p' so that the total weight is 5 grams. Adjust Q till PQ is again

horizontal, and mark the point S. Carefully measure QS. Increase the weight w, so that $(w+p)$ is 10 grams, and repeat the previous process, also when $(w+p')$ is 15 grams, and so on. In this experiment the *deflecting force* (F) is the weight $(w+p')$, and the angle QOS is the *angle of deflection*. Tabulate your results in the following manner:—

SQ	$(w+p)$	Tangent of QOS* $=\frac{SQ}{OQ}$	$\frac{w+p'}{\tan QOS}$.

From these results the following rule may be deduced:—*The tangent of the angle of deflection is proportional to the deflecting force.* (This is usually termed the *Tangent Law*.)

(iii.) **Direction of the Resultant Force.** The same apparatus may be used to prove that the direction taken up by the string OS coincides with that of the resultant of the two forces $(W+p)$ and $(w+p)$.

When $(w+p)=5$ grams, mark a distance Sa proportional to $(w+p')$ in any suitable scale (making, say, 1 cm to represent 1 gram). Similarly mark a distance Sb to represent the force $(W+p)$ to the same scale. Complete the parallelogram Sacb, and draw the diagonal Sc. Produce OS by means of a straight edge, and note how closely it coincides with Sc. Repeat these observations for the other values of $(w+p')$.

The Tangent Law holds good with magnetic forces as well as with gravitational force. In any given position the earth exerts a constant force on the poles of a magnetised needle, which tends to remain pointing in one definite direction. Other magnetic forces may be compared by

* A table of the arithmetical values of the tangents of angles from 1° to 90° is inserted at the end of the book (pp. 230, 231).

observing the angle of deflection which they successively cause when placed east or west of the needle. This principle may be used to determine how the magnitude of the force varies with the distance of its source from the needle upon which it is acting.

16. The Law of Inverse Squares

Apparatus required.—Magnetometer (see note 4, p. 216). Magnetised knitting-needle (at least 45 cms. long).

(i.) Adjust the magnetometer so that the pointer is over the zero of the circular scale, and place the magnet on the right hand scale, with its near pole 15 cms. from the needle,

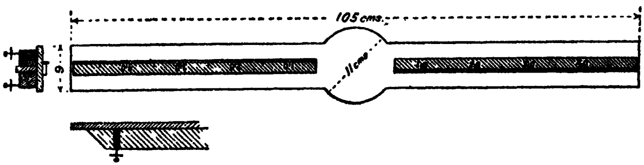


FIG. 9.—Construction of a magnetometer.

and note the deflection (by reading both ends of the pointer, and taking the mean of these readings). Repeat these readings with the magnet on the *left* hand scale, and at the same distance from the needle.

Carry out the same experiment at distances 20 cms., 25 cms., etc.

Record your observations in the following manner:—

Distance.	Deflections.	Mean Deflection, θ.	tan θ.	tan $\theta \times (\text{distance})^2$.
15 cms.	(i.) (ii.) (iii.) (iv.)			

In this experiment we know that the force is proportional to the tangent of the angle of deflection. If the product (tan $\theta \times$ distance) were a constant quantity, we should conclude that the force *varied inversely* as the distance. But, in this case, we find that a constant quantity is given by the product (tan $\theta \times (\text{distance})^2$); which proves that *the force varies inversely as the square of the distance.*

Additional Exercises

1. Two long magnets are placed vertically with their north poles (A and B) at the same level as the north pole (C) of a compass-needle, one being magnetic east and the other magnetic west of C. If the compass is not deflected when the distance AC is twice BC, and if all the magnets are so long that the effects of their south poles may be neglected, show what are the relative strengths of the poles A and B. (1887.)

2. A compass-needle is suspended at the centre of a circle drawn on a horizontal table. A magnet is moved round the compass so that its centre always lies on this circle, and that its length always points magnetic east and west. How and why will the position of the compass-needle change as the magnet is carried round it? (1887.)

CHAPTER IV

The Poles of a Magnet, and the Resultant Magnetic Field

17. The Poles of a Magnet

Apparatus required.—Magnetised needle. Short bar-magnet. Iron filings. Compass-needle. Drawing-board and sheet of paper. A straight-edge.

(i.) **Magnetic Poles.**—Dip a magnetised needle into iron filings. Note how the filings cling to the extreme ends (which are termed the *poles*).

(ii.) **Magnetic Regions.**—Repeat Expt. 17 (i.) with a short bar-magnet. Note how the filings now cling chiefly to the ends, but that some also adhere even at a considerable distance from the ends. The *poles*, in this case, do not appear to be well-defined *points*, but rather *regions* of magnetic attraction.

The poles may be defined as the points of application of the resultant forces of attraction and repulsion which the magnet exerts on any magnet pole near to it.

According to this definition the poles may be located by means of the fact that a compass-needle points with its axis in the direction of the resultant magnetic force at the point where it is situated.

(iii.) **Position of the Poles.**—Lay a bar-magnet on a sheet of white paper stretched on a drawing-board, and mark its position by passing the point of a pencil round its edges

(Fig. 10). Place a compass-needle at n_1s_1, and put pencil marks in line with its poles to indicate on the paper the direction in which it is pointing; repeat at n_2s_2 and n_3s_3. Remove

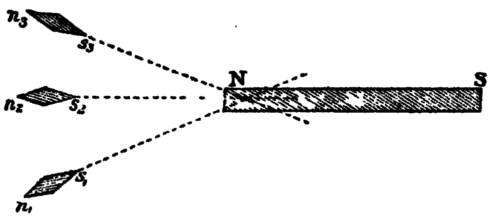


FIG. 10.—Method of localising the pole of a magnet

the magnet, and produce by means of a straight-edge the three directions obtained. The point of intersection of these lines indicates the position of the pole of the magnet.

A slight error is introduced if, in any of the selected positions, the compass-needle is not pointing due north, since the magnetic force due to the earth will make the needle point in a direction slightly different to that which would be due to the magnet alone

(iv.) Repeat Expt. iii., but take the precaution to rotate the board so that the needle always points due north. Observe whether the pole occupies the same position in both experiments (iii. and iv.). Note what fraction of the whole length of the magnet is the distance between the pole and the extreme end.

18. The Direction of the Resultant Force due to both Poles of a Magnet

Apparatus required.—Bar-magnet. Compass-needle. Metre scale. Parallel ruler. Drawing-board and sheet of paper.

(i.) Place the bar-magnet on the sheet of paper; mark its outline in pencil, and indicate the position of its poles by

pencil dots. Select any point n (Fig. 11) near to the magnet: join Nn and Sn, and measure their lengths. If a single north-seeking pole were placed at n, it would be attracted by S

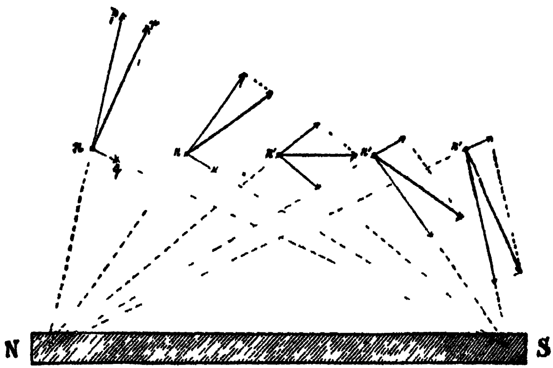


FIG. 11.—Method of determining the magnetic forces due to a bar-magnet.

and repelled by N, the relative magnitudes of these forces being inversely proportional to the squares of the distances. Calculate the values of $(Nn)^2$ and $(Sn)^2$. Then

$$\text{Attraction by S : Repulsion by N} :: (Nn)^2 : (Sn)^2.$$

Mark off distances nq and np, proportional in any suitable scale to $(Nn)^2$ and $(Sn)^2$.

Complete the parallelogram $nprq$, and draw the diagonal nr; this diagonal represents the direction of the resultant magnetic force due to N and S. The resultant force acting on a single *south*-seeking pole would act along the same diagonal, but in the reverse direction; hence a short compass-needle will come to rest pointing along the diagonal. Verify this by replacing the bar-magnet on the pencil outline; place the compass-needle with its centre over the point n, and rotate the board till the needle points due north.

Repeat the experiment for other points near to the magnet.

Additional Exercises

1. Determine, by the method of Expt. 17 (iii.), the position of the pole of (i.) a long knitting-needle strongly magnetised; (ii.) a shorter and broader magnet; (iii.) a still shorter magnet.

Note what fraction of the whole length of the magnet is the distance between the pole and the extreme end.

CHAPTER V

MAPS OF MAGNETIC FIELDS

19. Horizontal Map of the Earth's Magnetic Field

Apparatus required.—Large sheet of paper. Compass-needle.

(i.) Fasten a sheet of white paper (80 cms. x 60 cms.) on a table, with one edge pointing approximately north and south. Mark off one of the edges pointing east and west into spaces about 5 cms. wide. Place a sensitive compass-needle so that one of its poles is just over one of the marks, and indicate by means of a pencil mark the direction in which the other pole is pointing. Move the needle until its first pole is exactly over the second pencil mark; continue this process of marking the directions of the compass-needle until a series of marks have been obtained completely across the paper. Join up these points by a continuous pencil line. Plot out other lines in a similar manner, in each case starting from one of the equidistant pencil marks at the edge of the paper. Indicate by means of arrow-heads the direction in which the north-seeking pole of the compass-needle *tends* to move; this is called *the positive direction of the magnetic field.*

The diagram obtained is a *horizontal* map of the earth's magnetic field, so far as the limits of the paper will allow. Faraday, in 1837, termed the lines so obtained *lines of*

* Since considerable time is required in order to trace out the maps described in Expts. 19 and 20 it is advisable to allow two students, each with a compass-needle, to work together at different portions of the same map.

magnetic force, *i e* lines which indicate the direction in which the magnetic forces are acting.

20. Maps of the Resultant Magnetic Fields due to a Bar-magnet and the Earth

Apparatus required.—Large sheets of paper. Bar-magnet. Compass-needle.

(1) **With the North-seeking Pole of the Magnet pointing towards the South.**—Fasten a sheet of paper on the

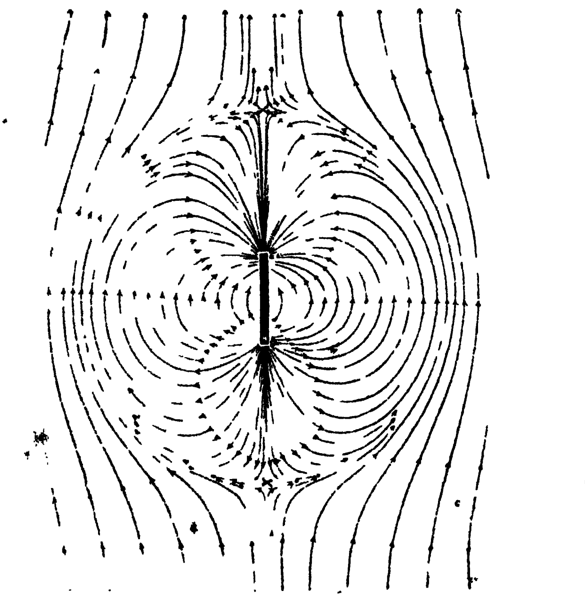


FIG 12.—Map of the combined field due to the earth and a bar magnet (N pole pointing south)

table in the same manner as in Expt. 19 (1) Determine accurately the north and south line by the compass-needle, and place a bar-magnet at the centre of the paper with its axis pointing north and south (north-seeking pole pointing south). Starting from a series of equidistant points marked along the

top edge, map out the lines of force in the same way as before (Fig. 12).

Observe that the lines of force near to the magnet appear to emerge from the north-seeking pole, tracing out a curved path and re-entering the magnet at its south-seeking pole. At greater distances the lines of force appear to be those due to the earth, which have been distorted by the presence of the magnet. Also observe that there are two regions (*marked* X) in which the magnet's effect is exactly neutralised by that of the earth, and in which the needle will consequently come to rest in any position with equal readiness; these regions are termed *neutral points*.

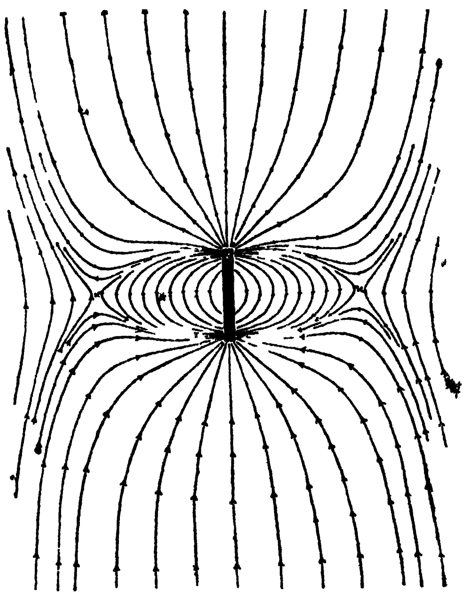


FIG. 13.—Same as Fig. 12, but with N. pole pointing north.

(ii.) **With the South-seeking Pole of the Magnet pointing towards the South.**—Conduct the experiment in exactly the same manner as described in Expt. 20 (i.).

Fig. 13 indicates the general character of the map which should be obtained.

Observe how the lines of force due to the earth appear to be drawn together by the magnet, and how the more distant lines are distorted. The neutral points are now east and west of the magnet.

(iii.) **With the Axis of the Magnet lying East and West.**—Repeat the preceding experiment, with the magnet lying east and west.

21. Iron-filing Maps of Magnetic Fields

Apparatus required.—Pair of bar-magnets. Horse-shoe magnet. One cylindrical bar-magnet. Iron filings. Strips of wood of same thickness as magnets. Paraffined paper (see note 5, p. 217). Bunsen burner.

Accurate maps of the field *near* to a magnet may be obtained by means of iron filings, the method depending upon the principle of magnetic induction whereby a piece of soft iron, when placed in a magnetic field, becomes magnetised by induction. Soft-iron filings may be used for the purpose; each fragment will become a temporary magnet, and, if free to move, will behave in the same manner as a compass-needle.

Obtain maps of the magnetic fields due to the following arrangements of magnets :—

(i.) **One bar-magnet** (Fig. 14).—Lay a piece of paraffined paper over the magnet, and support the edges of the paper, if necessary, with strips of wood so as to keep it as horizontal as possible. Sprinkle iron filings, contained in a gauze bag or pepper-box, uniformly over the paper. Gently tap the paper until the filings have taken up a definite position. Melt the upper surface of the paraffined paper by means of a Bunsen flame, and allow the paper to cool.

Obtain maps of the following in the same manner.

(ii.) Two bar-magnets, side by side, with unlike poles together.

(iii.) Two bar-magnets side by side, with like poles together.

(iv.) Two bar-magnets, with their axes in line, and unlike poles together.

(v.) Two bar-magnets, with their axes in line, and like poles together.

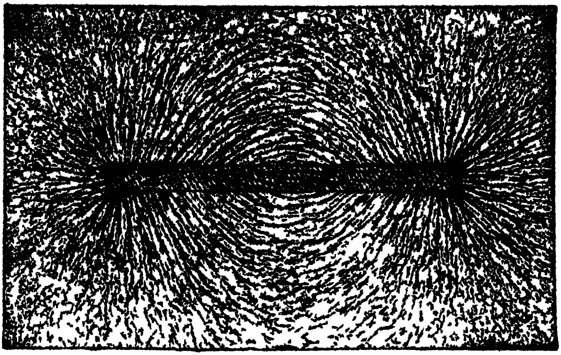


FIG. 14 —Magnetic field round a bar magnet.

(vi.) One horse-shoe magnet.

(vii.) One cylindrical bar-magnet, fixed in a vertical position, and the paper supported horizontally over the upper pole.

22. Vertical Map of a Magnet's Field

Apparatus required.—Large bar-magnet. Small sewing-needle. Silk fibre Wooden clamp. Spiral of wire and battery for magnetising needle.

(i.) Attach a silk fibre to a small sewing-needle and adjust the fibre so that the needle is exactly horizontal when swinging freely. Magnetise the needle by placing it inside a spiral of wire through which an electric current is passing. Clamp a large bar-magnet in a horizontal position and support the needle vertically over, and under, the magnet in a series of different positions. It will be evident that the general contour of the vertical magnetic field is the same as that of the horizontal.

In fact, ***the distribution of the lines of force is the same in all other planes as well as in the horizontal and vertical.***

23. Physical Attributes of Magnetic Lines of Force

Apparatus required.—Bar-magnet. Two sewing-needles.

A very instructive analogy, due to Faraday, compares the properties of magnetic lines of forces to the forces which would be exerted by stretched elastic threads (coinciding in direction with the lines of force), which tend to shorten from end to end and to repel one another from side to side. It is also important to notice that lines of force always connect regions of *opposite* magnetic polarity. Verify the above analogy by the following simple experiments :—

(i.) **Tendency of Lines of Force to shorten.**—Magnetise two sewing-needles and lay them on a smooth table, parallel to each other and about 1 cm. apart, with unlike poles together. Notice how the needles immediately roll towards each other. Draw a simple diagram of the magnetic lines of force between the two needles, and describe how the diagram explains the reason why the needles should roll towards each other.

(ii.) **Repulsion of Lines of Force.**—Place the two needles side by side and in contact with each other, and with *like* poles together. Observe the separation which takes place as soon as the needles are free to move. Sketch the lines of force, and explain the effect observed.

24. Tendency of a Single Magnet-pole to travel along a Line of Force

Apparatus required.—Large shallow dish. Long bar-magnet. Sewing-needle. Piece of cork.

(i.) Support a bar-magnet, 20 cms. long, near and parallel to the edge of a large photographic dish filled with water. Magnetise a short fragment of sewing-needle, and fix it through a small piece of cork so that the needle can float freely in a vertical position. Let the north-seeking pole of the needle be uppermost. If floated near to the north-seeking pole of the magnet the repulsion of the similar pole of the needle will be stronger than the attraction of the opposite pole of the needle, since the latter is more distant. The needle will slowly travel

over the surface of the water, tracing out a curved path connecting the north- and south-seeking poles of the magnet.

25. Lines of Equal Magnetic Potential

Apparatus required—Two bar-magnets. Compass-needle with cross bar Sheet of paper

A single magnet-pole tends to move along any line of force in a definite direction, and work has to be done on the pole in order to move it along the line of force in the opposite direction But no work is necessary in order to move it at right angles to a line of force, and lines may be drawn, in any magnetic field, which will indicate the directions in which a magnet pole may be moved without the expenditure of any work Such lines are called *Lines of Equal Magnetic Potential* These lines may be readily mapped out by means of a compass-needle provided with a short brass cross-bar, fixed at right angles to its length *

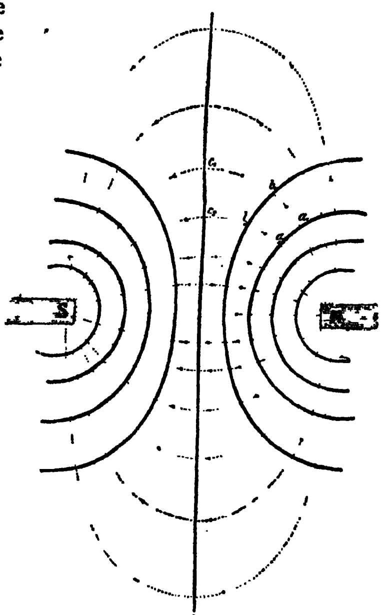


FIG 15—The thick lines indicate lines of equal magnetic potential

(1) Place two bar magnets on a sheet of paper with their axes in line, and with unlike poles about 10 cms. apart (as

* An excellent compass-needle of this pattern may be obtained from Messrs Philip Harris & Co, Edmund Street, Birmingham.

shown in Fig. 15). Map out about seven or eight *lines of force* by means of the needle, and the same number of *lines of equal potential* by means of the *cross-bar*. The former are represented in the figure by dotted lines, and the latter by continuous lines. *A line of equal potential is everywhere at right angles to the magnetic force.*

Additional Exercises

1. Map out, by the compass-needle method, the resultant magnetic field due to the earth and a bar-magnet, when the axis of the bar-magnet makes an angle of 45° with the magnetic meridian.

2. Map out, by the compass-needle method, the resultant field due to the earth and two bar-magnets, which are placed parallel to one another, 20 cms. apart, with their axes in the magnetic meridian and *unlike* poles together.

3. Repeat Question 2, but place the magnets with *like* poles together, and with the north-seeking poles towards the south.

4. Repeat Question 3, but place the magnets with their south-seeking poles towards the south.

5. Obtain a map, by the iron-filing method, of the field due to two bar-magnets placed at right angles to each other and not in contact, the axis of one passing through the middle point of the other.

6. Place a bar-magnet on the table with its axis in the magnetic meridian, and with its south-seeking pole towards the south. Find the direction in which a compass-needle points when held immediately above the magnet, and observe whether the direction alters as the needle is gradually raised vertically upwards. Can you detect a neutral point? If so, measure its distance vertically above the needle. Find the positions of the neutral points east and west of the magnet, and measure their distances from the magnet.

7. Iron-filings are scattered on a piece of cardboard which is placed over a horse-shoe magnet and tapped. What differences would be observed in the arrangement of the filings

when the ends of the magnet were joined in turn by bars of (1) steel, (2) soft iron, and (3) copper? (1896.)

8. Map out, by means of a compass-needle, about 8 or 10 lines of force in the field due to a single bar-magnet. Also, map out the same number of lines of equal magnetic potential.

9. Lay on a sheet of paper a strip of unmagnetised soft iron (about 30 cms. × 4 cms.) with its axis in the magnetic meridian. By means of a compass-needle map out the directions of the lines of force of the earth's field in the regions near to the ends of the iron.

CHAPTER VI

THE EARTH'S MAGNETIC FIELD

26. Induction due to the Earth's Field

Apparatus required.—Narrow strip of galvanised iron (about 40 cms. long). Compass-needle.

(i.) Hold a strip of thin galvanised iron so that it is pointing approximately north and south. Tap it gently with the knuckles. Test its polarity by bringing its ends near to a compass-needle. The end pointing towards the north has acquired north-seeking polarity. Now hold the iron with its north-seeking pole pointing towards the south, and again tap it. Notice that its polarity is now reversed. Finally, hold the iron in an east and west position and again tap it. Notice that all polarity has disappeared.

The tapping may even be dispensed with if the soft iron is simply kept in position and the compass-needle is brought near to its ends in order to detect the polarity.

Evidently there are lines of magnetic force originating from a region of north-seeking polarity in the neighbourhood of the south geographical pole, and traversing the earth's surface towards a region of south-seeking polarity in the neighbourhood of the north geographical pole.

27. The Lines of Force due to the Earth are not Horizontal

Apparatus required.—Long unmagnetised knitting-needle. Silk fibre. Sealing-wax. Bar-magnet.

(i.) Suspend a long knitting-needle by *tying* a silk thread to

it, and adjust the thread so that the needle swings horizontally. Carefully magnetise the needle without disturbing the position of the thread. Observe that the needle now dips down with its north-seeking pole downwards.

Since the needle naturally tends to take up a position *along the lines of force*, it follows that the latter must be inclined to the horizontal.

The angle between the axis of a magnetised needle, which is free to move in the vertical plane of the meridian, and the horizontal line through its point of support is called the Dip.

28. Determination of the Magnetic Meridian

Apparatus required.—Bar-magnet. Suspension. Two square pieces of thin cardboard. Soft wax. Pins.

(i.) Bore circular holes through two square pieces of cardboard, and fasten silk fibres across the holes (Fig. 16). Attach these to opposite end-faces of a bar-magnet, and suspend the magnet above the table by means of a silk loop and a bundle

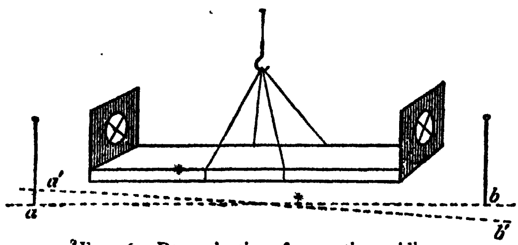


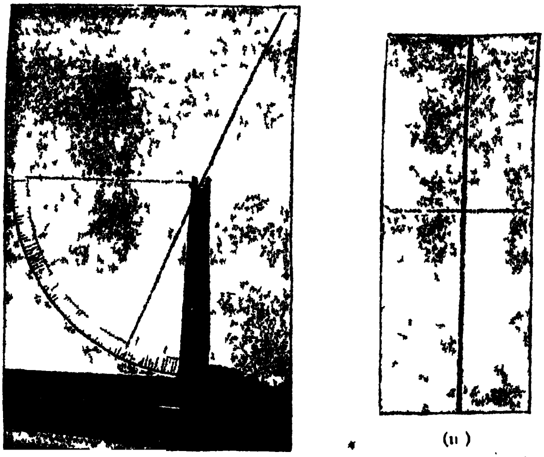
FIG. 16.—Determination of magnetic meridian.

of unspun silk fibres. Bring the magnet to rest, and mark the direction of the line *ab* joining the points of intersection of the silk fibres by means of *brass* pins fixed into the table. Reverse the magnet so that the cross-fibres are now below the magnet, and mark the direction *a'b'*. The line bisecting the angle between *ab* and *a'b'* is the *magnetic meridian*. Also, since the magnet comes to rest with its *magnetic axis* coinciding with the magnetic meridian, a line drawn on the face of the magnet in the same vertical plane as the meridian will indicate the direction of the magnet's magnetic axis.

29. Simple Dip Needle

Apparatus required.—A simple form of Dip needle (see note 6, p. 217).

(i.) Place the needle on the knife edges with its axle coinciding with the centre of the circular scale. Determine the magnetic meridian by means of a compass-needle, and mark the direction of this on the table. Place the needle so that it



(i.) (ii.)

FIG. 17.—A simple form of dip needle.

swings freely in the vertical plane of the meridian. Observe the angle of dip. Make the needle swing slightly and again observe the dip. Repeat several times. Enter each observation in your note-book, and determine the average value of the dip.

30. Determination of Dip, by Induction in Soft Iron

Apparatus required.—Long strip of galvanised iron. Magnetometer.

When a piece of soft iron is held in the earth's field, the maximum degree of magnetisation is obtained when the iron is held so that its axis points *along* the lines of force. But the total force in this direction may be regarded as the resultant of two weaker forces, one horizontal, and the other vertical. In Fig. 18, *n*I represents the magnitude and direction of the force acting on a single north-seeking pole, *n*. If the iron is held horizontally the degree of magnetisation will depend directly upon the magnitude of the horizontal force *n*H; if held vertically, the magnetisation will depend upon the magnitude of the vertical force *n*V.

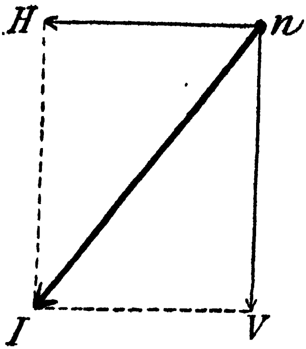


FIG. 18.—Horizontal and vertical components of a magnetic force.

But $\frac{nV}{nH} = \frac{HI}{nH}$ = the tangent of the angle of Dip (H*n*I).

The degree of magnetisation in these two positions may be compared by comparing the forces which the iron exerts on a magnetometer needle, assuming that the distance between the iron and the needle is the same in each case.

(i.) Place the magnetometer with its cm. scale at right angles ɔ the meridian. Test the galvanised iron to verify its freedom om permanent magnetisation. Hold the iron vertically with s lower end touching the scale of the magnetometer, and bout 7 cms. distant from the needle. Note the deflection and ıe distance. Remove the iron and carefully demagnetise it by ıpping while held east and west. Hold the iron horizontally the meridian with its northern end at the same distance from e needle as before. Note the deflection. Reverse the ends the iron and repeat the observations. Bear in mind that e forces are proportional to *the tangent of the angle of deflecm.* Tabulate the results as follows :—

	Vertical Position		Horizontal Position		$\frac{(2)}{(4)}$ = Tangent of Angle of Dip	Dip
	(1) Deflection	(2) Tangent of (1)	(3) Deflection	(4) Tangent of (3)		
1.						
2.						

31. Accurate Determination of Dip *

Apparatus required.—An accurate form of Dip circle. Pair of bar-magnets.

Theory of Adjustments.—The observations must be carried out systematically in order to avoid the following possible errors:—

(*a*) *The line joining the* 90° *reading on the upper and lower scale may not be vertical*—This error is corrected by taking one reading when the needle is in position, the instrument is then turned through 180° (by means of the horizontal scale) so as to bring the needle into different quadrants of the vertical circle; if the needle reads too low in the first case, it will now read too high, and the error is corrected by taking the mean of these readings.

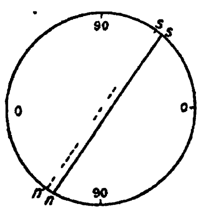


FIG. 10.

(*b*) *The needle's axle may not coincide with the centre of the scale.*—Let *ns* (Fig. 19) represent the axis of the needle, giving scale readings at *n* and *s*. The correct readings should be *n′* and *s′*. The error is corrected by reading both *n* and *s*, and taking the mean of these readings, for it is evident from the figure that, if the reading *n* is too high, the reading of *s* is too low to an equal extent.

* The experiment, as here described, can only be carried out in detail with an elaborate type of instrument which is seldom available in Elementary Physical Laboratories With simpler instruments the numerous adjustments are scarcely justifiable, but their strict observance by the student would still be highly instructive.

(*c*) *The magnetic axis does not coincide with the axis of figure.*—Let $n's'$ (Fig. 20, I.) represent the magnetic axis of the needle ns. The readings n and s are incorrect—they are

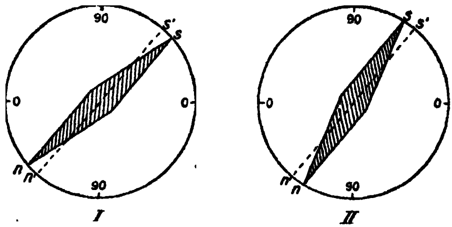


FIG. 20.

both too low. If the needle is reversed in its bearings (Fig. 20, II.), then both readings are too high. The error is therefore corrected by taking the average of these four readings.

(*d*) *The centre of mass may be situated to one side of the centre of motion.*—In the position indicated in Fig. 21, I., this error will cause the reading to be too high. But if the needle

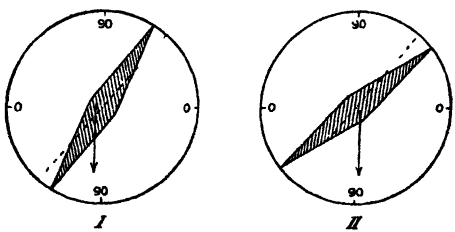


FIG. 21.

is reversed in its bearings, as shown in Fig. 21, II., the reading will be too low. The correct reading is obtained by taking the mean of the two readings.

(*e*) *The centre of mass may be displaced along the axis of the needle.*—This error is removed by reversing the poles of the needle. For if, in the first observation, the centre of mass should be above the axis of motion (Fig. 22, I.), thus causing the dip to diminish, the reversal of the poles will bring the centre of mass below the axis of motion (Fig. 22, II.), thus

causing the dip to increase. The mean of these readings eliminates the error.

(i.) **Determination of the Magnetic Meridian.**—This is determined by rotating the plane of free motion of the needle

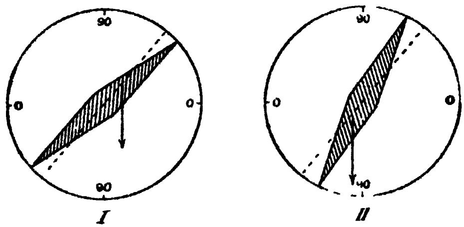


FIG. 22

until the needle is vertical. This position indicates that the needle is only influenced by the vertical component of the earth's magnetic force—the horizontal component is only *tending* to strain the axle of the needle. If the needle is now rotated through 90°, as observed on the horizontal scale, the plane of free motion will coincide exactly with the magnetic meridian.

All the liable errors, except (*e*), are involved, and they are eliminated by taking the following eight readings:—

Face of Instrument.	Face of Needle.	Readings of horizontal scale, when needle points to 90°.
South . .	South . .	North pole (i.)............... South pole (ii.).............
	North . .	(iii.)............ (iv.)............
North . .	South . .	(v.)............ (vi.)............
	North . .	(vii.)............ (viii.)............

Take the mean of these readings, θ, and rotate the

instrument until the scale-reading is $(90+\theta)$. The plane of free motion of the needle now coincides with the magnetic meridian.

(ii.) **Determination of the Dip.**—Commence with the instrument facing *east*, and with the needle also facing *east;* read both poles of the needle. Reverse the needle on its bearings, so that it now faces *west*, and read both poles. Rotate the instrument through 180°, so that it now faces *west;* read both poles. Reverse the needle on its bearings, and again read both poles. So far eight readings have been obtained, but the liable error (e) has not been eliminated. The polarity of the needle must now be reversed by the method of "double touch," and all the previous observations repeated. Tabulate the results in the following manner:—

Face of Instrument.	Face of Needle.	North Pole South Pole.	North Pole. South Pole. (Polarity reversed.)
East	East .	....	....
	West .	....	....
West .	East .	....	....
	West .	....	....

The true Dip is obtained by calculating the mean value of these observations.

ADDITIONAL EXERCISES

1. The axis, about which a dipping needle is movable, is slowly rotated in a horizontal plane. Describe and explain the behaviour of the needle during one complete turn of the axis. (1894.)

2. A bar of soft iron lies on a table at right angles to the magnetic meridian, and a compass-needle is placed at some distance from the bar with its centre on the axis of the bar produced. The end of the bar nearest to the needle being

kept in the same position, the bar is then turned round, upon the table, until it is parallel to the magnetic meridian, the fixed end of the bar being to the south. Describe the behaviour of the compass (1) before, (2) during the rotation of the bar. (1896.)

3. A dipping needle can oscillate in the magnetic meridian. A long bar of soft iron held horizontally in a north and south direction is brought near to it from the south. How is the inclination of the needle to the horizon affected as the distance between it and the bar is gradually diminished? (1892.)

4. A rod of iron when brought near to a compass-needle attracts one pole and repels the other. How will you ascertain whether its magnetism is permanent or is due to temporary induction from the earth? (1891.)

5. What effect (if any) is produced (1) on the weight, (2) on the position of the centre of gravity, of a piece of steel by magnetising it? Give reasons. (1887.)

6. By means of a steel disc, magnetised along any unknown diameter, and a suitable suspension determine (1) the magnetic meridian, and (2) the direction of the magnetic axis of the disc.

7. If the direction of the magnetic meridian is known, how would you determine the magnetic axis of a magnetised steel sphere? If the direction of the meridian is not known, what further observations would be necessary in order to determine both this direction and that of the magnetic axis of the sphere?

CHAPTER VII

INTERNAL MAGNETIC FIELDS

32. Magnetic Lines of Force inside a Magnet

Apparatus required.—A long piece of magnetised watch-spring. Iron filings. Paraffined paper. A test-tube fitted with cork, and filled with steel filings. A strong bar-magnet. Compass-needle.

(i.) Break a piece of magnetised watch-spring into three or four pieces, and place them on the table in line and with a short space interval between the broken ends. Make an iron-filing map of the magnets (by the method described in § 21). Notice how the consecutive broken ends appear to be connected together by lines of force. It would appear as though the whole length of the magnet were traversed by lines of force, which at one end emerge from the north-seeking pole and re-enter at the south-seeking pole, thus forming complete loops.

The same result would be obtained if the magnet were broken into a far larger number of fragments. In fact we may assume that the smallest possible fragment—the *molecule*—of a bar-magnet is a minute magnet in itself. We can imitate the process of magnetisation in the next experiment.

(ii.) Fill a glass test-tube with steel filings loosely packed; cork up the tube, and notice that it behaves towards a test-needle like an ordinary piece of iron. Magnetise the tube by single touch, or better, by means of a spiral of wire and electric current (§ 2, iii.). Observe that the tube now has opposite polarities at its two ends, and that the filings appear

to some extent to have arranged themselves lengthwise. Each filing has been magnetised, just as small sewing-needles would have been magnetised by similar treatment. Each filing has its lines of magnetic force, which come from, and afterwards pass into, neighbouring filings, and which only appear at the ends of the tube where they emerge into the surrounding space.

Empty the filings out on to a sheet of paper, mix well together, and pour them back into the tube; again test for polarity.

The polarity has been destroyed, and the tube again behaves like an ordinary piece of iron.

By mixing the filings together higgledy-piggledy the magnetism of each filing is masked by that of neighbouring filings, which group together to form a number of so-called "closed magnetic chains."

33. Open and Closed Magnetic Chains

Apparatus required.—Three sewing-needles, magnetised to an approximately equal degree. Several small compass-needles. Iron filings, and paper. Bar-magnet.

(i.) **Closed Magnetic Chains.**—Place two equally-magnetised darning-needles side by side, with unlike poles together. Take a map of the magnetic field with iron filings. Observe the behaviour of a compass-needle at various points in the neighbourhood. At a distance the whole arrangement behaves like a mass of unmagnetised iron.

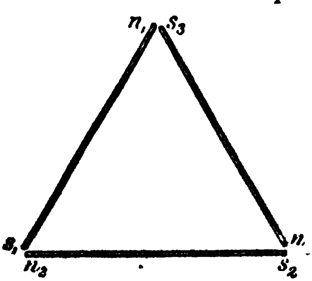


FIG. 23.—Three magnets forming a closed magnetic chain.

(ii.) Arrange three needles as shown in Fig. 23. Use the compass-needle in order to find whether any external magnetic force can be detected in the space near to the needles.

Under suitable conditions each line of force traverses the sides of the triangle taken in order, and no lines are found

externally. Any such arrangement as that described in Expts. i. and ii. is termed a *closed magnetic chain*.

(iii.) **Open Magnetic Chains.**—Arrange the needles as shown in Fig. 24, and repeat Expt. ii. An external magnetic field should be found between n_1 and s_3. Determine the general direction of the lines of force, and indicate this by means of a diagram.

Any such arrangement as this is termed an *open magnetic chain*.

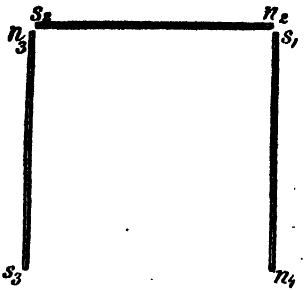


FIG. 24.—An open magnetic chain.

These experiments explain how the filings, in Expt. 32 (ii.), may remain magnetised, and yet show no external signs of their magnetisation. If the tube of filings is again magnetised, the "closed chains" will be broken up, and the filings will tend to arrange themselves in line, with similar poles all pointing in the same direction.

(iv.) **Behaviour of Soft Iron in a Magnetic Field.**—Place a group of ten or twelve small compass-needles as close together as possible. Make a diagram showing the directions in which the needles are pointing. Place a bar-magnet on the table, with its pole about 15 cms. away from the group. Make another diagram of the needles. Repeat with the magnet still nearer (say 10 cms. away). Notice how, as the magnet approaches, the needles tend to point more and more in the same direction. Now remove the magnet to a distance, and note how the needles swing back into their original grouping. This experiment resembles the behaviour of a piece of soft iron when placed in a magnetic field.

34. The Effect of Soft Iron on the Field of a Bar-magnet

Apparatus required.—Bar-magnet. Bar of soft iron. Iron filings. Paraffined paper.

(i.) Place the bar of soft iron near to the bar-magnet, as shown in Fig. 25. The soft iron is temporarily magnetised, with south-seeking polarity at the end D. The magnetic field of the bar-magnet is also affected. Make an iron-filing map of the arrangement. Note how the distant side of the soft iron appears to be "screened" from the influence of the bar-magnet.

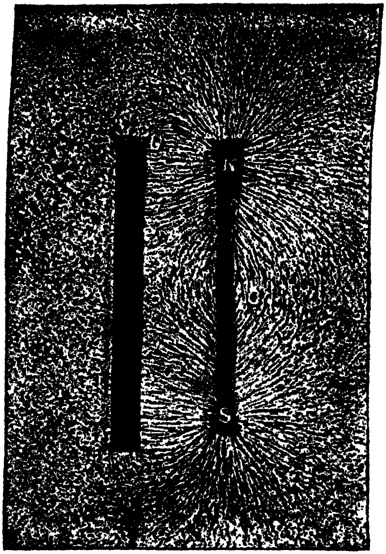


FIG. 25.—A bar of soft iron placed near to a bar-magnet.

35. Magnetic Screens

Apparatus required.—Bar-magnet. Magnetometer. Thick slab of soft iron.

(i.) Support a bar-magnet on a wooden block about 20 cms. to the east or west of the magnetometer needle. Note the deflection. Interpose a slab of soft iron (2 cms. thick) and note the change of deflection. Place the slab in various positions and note the deflection in each case. Observe what position of the slab affords a maximum screening of the needle. (If a thick slab of soft iron is not available, the screening effect can be satisfactorily shown by using two or three thicknesses of galvanised iron sheet.)

ADDITIONAL EXERCISES

1. Two circular rings of iron are magnetised, the first by being placed between the poles of a strong horse-shoe magnet, so that the line joining the poles of the magnet is a diameter

of the ring, the second by having one pole of a bar-magnet drawn round it several times. Describe the magnetic state of each ring. (1894.)

2. A compass-needle is deflected by a bar-magnet placed some distance away from it. How is the deflection modified (if at all) when a bar of soft iron is placed parallel to, but not touching, the magnet? (1895.)

If the magnet is placed horizontally in the magnetic meridian due south of the compass-needle, how will its action on the latter be affected if (i.) a plate of soft iron is interposed between the two, (ii.) a rod of soft iron is placed along the line which joins their centres? (1891.)

magnet vibrating by bringing another magnet near to it for a moment. Note the time when the beam of light is observed to traverse the line of sight, and carefully count the number of subsequent passages *in the same direction* until 20 complete oscillations have been described (*i.e.* until the beam traverses the line of sight for the 21st time). Calculate the number of oscillations which would be described in one minute; call this number n_1. Repeat the observation at some other point of the room, and calculate the number of oscillations, n_2, described in one minute. Then if I_1, I_2 represent the magnetic intensities at the two places,

$$I_1 : I_2 :: n_1^2 : n_2^2.$$

37. Experimental Proof of the Law of Inverse Squares

Apparatus required.—Magnetoscope. Long bar-magnet. Metre scale.

(i.) Place the bar-magnet on the bench with its axis in the magnetic meridian and with its north-seeking pole towards the north. Place the magnetoscope at a point in line with the axis of the magnet and 15 cms. distant from the north-seeking pole. The forces due to the magnet and the earth act in the *same* direction, and the square of the number of oscillations will be proportional to the *sum* of the forces. In order to eliminate the effect of the earth's field, it is necessary to determine the number of swings due to the earth alone, and to subtract the square of this number from the square of the number described when the magnet is in position.

Observe n_1, at a distance of 15 cms. from N.
" n_2 " 10 cms. "
" n, when the magnet is removed to a distance.

Then if F_1 = force due to the magnet at a distance of 15 cms, and F_2 = force due to the magnet at a distance of 10 cms,

$$\frac{F_1}{F_2} = \frac{n_1^2 - n^2}{n_2^2 - n^2}.$$

If the Law of Inverse Squares is correct, then $\dfrac{F_1}{F_2} = \dfrac{d_2^2}{d_1^2}$.

Tabulate your results in the following manner :—

Distance.	Oscillations in One Minute.	n.	$\frac{n_1^2 - n^2}{n_2^2 - n^2}$.	$\frac{d_2^2}{d_1^2}$.
d_1	$n_1 =$			
$d_2 =$	$n_2 =$			

38. Equality of Strength of the two Poles of a Bar-magnet

Apparatus required.—Short bar magnet. Sheet of paper. Magnetoscope. Stop-watch.

(i.) Lay the bar-magnet on the sheet of paper, and adjust it so that the axis of the magnet is exactly in the magnetic meridian. Mark out two points on the paper and along the axis of the magnet produced, one of them north of the magnet, and the other to the south, and at the same distance from the magnet. Determine the time of vibration of the magnetoscope when placed at these points. The two poles of the magnet will be proved to be equal in strength if the time of vibration is the same at the two points.

39. The Distribution of Magnetism along a Bar-magnet

Apparatus required.—Long bar magnet. Magnetoscope. Metre scale. Two wooden clamps. Stop-watch. Squared paper.

(i.) **The Observations.**—Mark, by means of a pencil, the middle point of the magnet. Clamp the magnet vertically with its narrow edge facing due north, and with its north-seeking pole downwards. Remove the cork base of the magnetoscope, and support it vertically in a clamp, at such a height that the needle is at the same level as the middle point of the magnet. Place the magnetoscope as close as possible to the magnet and due north of it.

Remove the magnet to a distance, and determine the number of swings, n, described in one minute, due to the earth alone.

Replace the magnet in its original position, and again

determine the number of swings, n_1, described in one minute. Raise the magnet two centimetres, and again determine n_1. Proceed in this manner until six or seven independent observations have been made opposite different points of the bar-magnet, taking care in each case that the needle is at the same distance from the magnet. Tabulate your observations in the following manner :—

Vertical Distance.	n_1.	n.	$(n_1^2 - n^2)$.

(ii.) **Plotting the Results.**—Draw the outline of the magnet

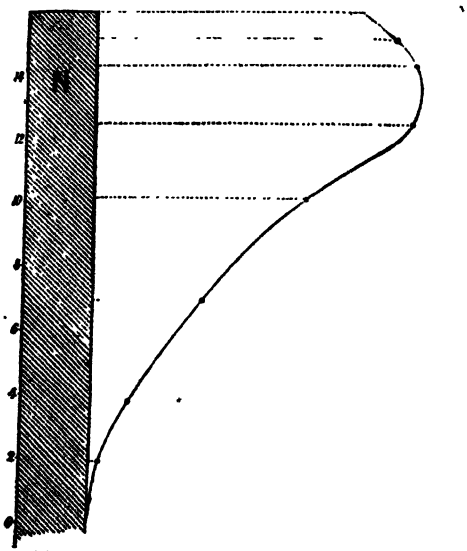


FIG. 27.—Diagram of the intensity of the field near to a bar-magnet.

on the squared paper, its length coinciding with the vertical lines. Mark the points opposite which observations were taken,

and measure horizontal distances from each point, the distance in each case being proportional to the numerical value of $(n_1^2 - n^2)$ for that point.

The curve joining the ends of these horizontal lines indicates how the magnetic intensity falls off towards the centre (Fig. 27).

40. The Rate of Swing of an Astatic Pair

Apparatus required.—An astatic pair, with mirror attached, suspended inside a beaker or wide-mouthed bottle. Stop-watch. Candle and "sighter."

If the two magnets, constituting the astatic pair (Fig. 28), have exactly equal pole strength then the pair will come to rest in any position, and will not be affected by the earth's field. In practice the pole strengths are seldom exactly the same, and the pair will behave like an extremely weak magnet, of which the pole strength is $m_1 - m_2$ (where m_1 and m_2 are the pole strengths of the two needles, m_1 being the stronger). If the lower needle is twisted through 180°, so that similar poles are pointing in the same direction, then they will behave like a single magnet of pole strength $m_1 + m_2$.

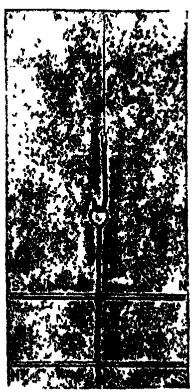


FIG. 28.—An astatic pair.

(i.) Determine the number of swings, n_1, described in one minute with the needles in their normal position. Twist the lower needle through 180°, and again determine the number of swings, n_2, described in one minute. Then

$$\frac{m_1 - m_2}{m_1 + m_2} = \frac{n_1^2}{n_2^2},$$

or,

$$\frac{m_1}{m_2} = \frac{n_2^2 + n_1^2}{n_2^2 - n_1^2}.$$

This ratio indicates the ratio of the pole strengths of the two needles.

41. Work done in moving a Magnet Pole from one Surface of Equal Potential to another

Apparatus required.—Drawing-board. Sheet of paper. Bar-magnet. Magnetoscope. Compass-needle (with cross-bar). Stop-watch.

In Fig. 29, let the continuous lines represent portions of lines of magnetic force, and the dotted lines represent lines of equal potential. The experiment is to prove that the work required in order to move a north-seeking pole from 1 to 2, or from 3 to 4, or from 5 to 6, is equal in each case.

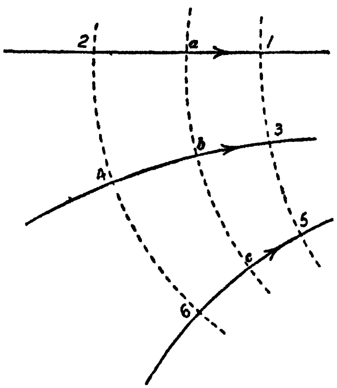


FIG. 29.

The work required = average force × *distance.*

We can obtain an approximate comparison of the average force by observing the rates of swing of the magnetoscope needle at the middle points *a*, *b*, and *c*.

(i.) Place the bar-magnet on a sheet of paper, and mark the outline of the magnet in pencil. Trace out, by means of a compass-needle, portions of three lines of forces, and of two lines of equal potential (as shown in Fig. 29). Determine, as carefully as possible, the middle points *a*, *b*, and *c*, and measure the length of the lines 1-2, 3-4, and 5-6; the *curved* lines may be measured more conveniently by using a narrow strip of paper, the long edge of which is made to trace out the curved line, and the required points marked in pencil.

Place the magnetoscope at point *a*, and determine the number of vibrations in one minute. Repeat this at the points *b* and *c*.

Tabulate your results in the following manner:—

Line.	Distance between Equipotential lines (d).	Vibrations in one minute (n).	($d \times n^2$).

The results show that *the work done in moving a magnet pole from one surface of equal potential to another is the same, whatever path is traversed.*

Additional Exercises

1. Compare by the method of vibration the two magnetic fields as arranged. (Inter. County Sch., L.C.C. 1900.)

2. A bar-magnet which can move only in a horizontal plane is caused to vibrate at three different stations, A, B, and C. At A it makes 20 vibrations in 1 minute 30 seconds; at B, 25 vibrations in 1 minute 40 seconds; at C, 20 vibrations in 2 minutes. Find three numbers proportional to the forces which act upon the magnet at the three places. (1888.)

3. If a soft iron pillar were buried vertically in the ground what effect would it produce on the times of vibration of two compass-needles to the north and south of it respectively? (1892.)

4. An iron pillar stands vertically in the centre of a room in which the direction of the magnetic meridian is known. Assuming that there is no other iron in the neighbourhood, how would you determine what part of the horizontal magnetic force at a given point in the room, magnetic north or south of the centre of the pillar, is due to the pillar? (1895.)

5. A bar-magnet is placed with its centre due east of a compass-needle, and with its axis parallel to the magnetic meridian. How will you determine whether the intensity of

the magnetic field at the needle is increased or diminished? Further, how will you compare the field with that which existed there before the bar-magnet was brought near? (1896.)

6. Two magnets are placed horizontally on a large sheet of white paper. You are supplied with a small compass, a pencil, and a watch. Assuming that the earth's field may be neglected, how would you trace the lines of force due to the magnets, and determine points at which the intensity of the magnetic field was equal? (1898.)

7. Compare the magnetic force due to a given magnet at two points, A and B. A is a point on the prolongation of the axis of the magnet, and B is a point on the line through the centre of the magnet at right angles to its axis. A and B are equally distant from the centre of the magnet. (Lond. B.Sc., 1896.)

8. Determine the rate of swing of the needle of a magnetoscope at any point. By repeating the observation determine to what extent the horizontal intensity of the earth's field is modified when a strip of unmagnetised soft iron (about 30 cms. × 4 cms.) is placed at different distances from the magnetoscope, and with its axis in the magnetic meridian and in line with the centre of the needle of the magnetoscope.

CHAPTER IX

MAGNETIC MOMENTS

When a magnet is swinging in the earth's magnetic field the force acting on each pole is represented by

$$F = m \times H. \quad \text{(See Chapter VIII.)}$$

Let *ns* (Fig. 30, I.) represent a swinging magnet, of which the pole strength is m', and let NS represent a bar magnet,

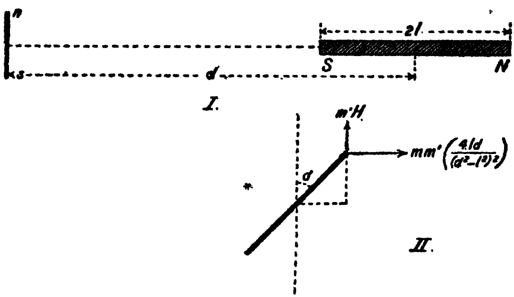


FIG. 30.

of which the length is $2l$, and pole strength m, and which is placed with its axis in line with the centre of *ns* and lying exactly east and west. Let d be the distance between the centres of NS and *ns*.

The force of *attraction* on n, due to S, $= \dfrac{mm'}{(d-l)^2}$, and

the force of *repulsion* on n, due to N, $= \dfrac{mm'}{(d+l)^2}$.

The *resultant* force on $n = mm'\left(\frac{1}{(d-l)^2} - \frac{1}{(d+l)^2}\right)$

$$= mm'\left(\frac{4ld}{(d^2-l^2)^2}\right).$$

The needle *ns* will be deflected through an angle α, such that

$$mm'\left(\frac{4ld}{(d^2-l^2)^2}\right)\Big/ m'\mathrm{H} = \tan\alpha \text{ (Fig. 30, II.)},$$

or,
$$\frac{4mld}{(d^2-l^2)^2} = \mathrm{H}\tan\alpha. \qquad \text{(i.)}$$

But, the *moment of the magnet* NS is defined as *the strength of one pole × length of magnet* $= m \times 2l$. This product is usually denoted by the symbol M.—Hence equation (i.) becomes

$$\frac{\mathrm{M} \times 2d}{(d^2-l^2)^2} = \mathrm{H}\tan\alpha,$$

or, $\frac{\mathrm{M}}{\mathrm{H}} = \frac{(d^2-l^2)^2}{2d}\tan\alpha$ (or, approximately), $\frac{d^3}{2}\tan\alpha$.

42. Comparison of the Moments of two Magnets by the Deflection Magnetometer

Apparatus required.—Deflection magnetometer (see § 16). Two small bar-magnets (marked A and B).

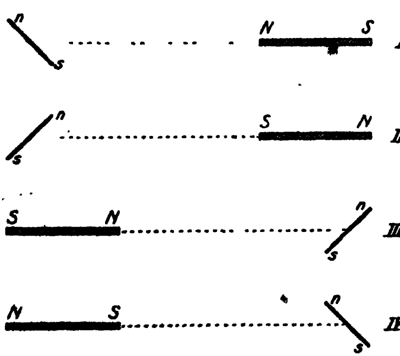


Fig. 31.

(i.) First Method.—Adjust the magnetometer so that its arms are perpendicular to the magnetic meridian. Place the bar-magnet (marked A) on the right-hand arm of the magnetometer, and with its centre 15 cms. away from the middle (Fig. 31, I.). Note the deflection. Reverse the magnet (Fig. 31, II.),

and again note the deflection. Repeat these observations when the magnet is on the left-hand arm of the magnetometer (Fig. 31, III. and IV.). Tabulate the observations in the following manner:—

d	Deflection in each Position.	Mean Deflection.	$\frac{(d^2-l^2)^2}{2d}\tan a$	$\frac{d^3}{2}\tan a.$
15 cms.	I. II. III IV			
20 cms.	I. II. III. IV.			

Take the mean value of $\frac{M_A}{H}$ in the fourth column, as the correct value.

Observe that less concordant results are obtained when the approximate formula, in the last column, is used.

Repeat these observations, using the magnet marked B, and calculate the value of $\frac{M_B}{H}$.

Calculate the ratio $\frac{M_A}{H}\Big/\frac{M_B}{H}=\frac{M_A}{M_B}$.

(ii.) **Second Method.**—The moments of the magnets A and B may also be compared in the following manner:—Place the two magnets on opposite sides of the magnetometer so that they simultaneously tend to deflect the needle in opposite directions. Alter the distances d_1 and d_2 until the deflection is zero. Then

$$\frac{M_A \times 2d_1}{(d_1^2-l_1^2)^2}=\frac{M_B \times 2d_2}{(d_2^2-l_2^2)^2},$$

or,

$$\frac{M_A}{M_B}=\frac{(d_1^2-l_1^2)^2 d_2}{(d_2^2-l_2^2)^2 d_1}.$$

43. Comparison of the Moments of two Magnets by the Method of Vibrations

Apparatus required.—Two bar-magnets (marked A and B, the same as used in § 42). Case in which to suspend magnets (Fig 32. See note 8, p. 218). Stop-watch, etc.

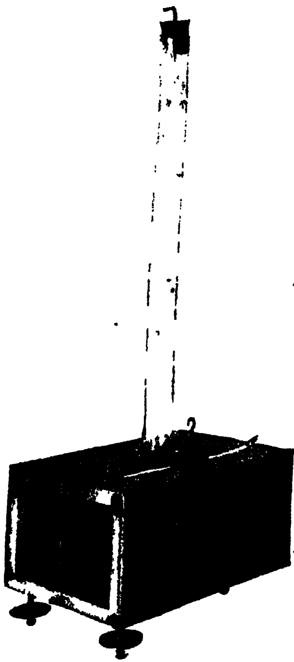


FIG. 32.—Box for determining vibration periods of magnets

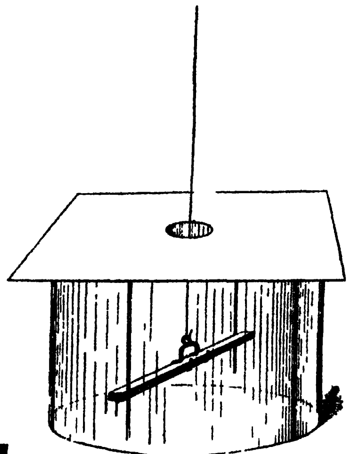


FIG 33.—Alternative method of suspending magnet.

If a magnet is swinging freely, the time of one complete oscillation is given by the formula

$$t = 2\pi\sqrt{\frac{I}{MH}},$$

or, $$MH = \frac{4\pi^2 I}{t^2},$$

(where I = the Moment of Inertia, which can be calculated from the weight and dimensions of the magnet).*

* For a cylindrical magnet, $I = \left(\frac{(\text{length})^2}{12} + \frac{(\text{radius})^2}{4}\right) \times \text{weight}.$

,, rectangular ,, $I = \left(\frac{(\text{length})^2 + (\text{breadth})^2}{12}\right) \times \text{weight}.$

(See Stewart and Gee's *Practical Physics*, vol. i. p. 242).

(i.) Carefully measure the dimensions and weights of the two magnets, and calculate their Moments of Inertia (I_1 and I_2). Determine the times occupied by one complete oscillation (t_1 and t_2).

Then $$M_A H = \frac{4\pi^2 I_1}{t_1^2},$$

and $$M_B H = \frac{4\pi^2 I_2}{t_2^2},$$

or, $$\frac{M_A}{M_B} = \frac{I_1}{t_1^2} \times \frac{t_2^2}{I_2}.$$

Tabulate your observations in the following manner :—

Moments of Inertia	Time of one Complete Vibration	$\frac{I_1}{t_1^2} \times \frac{t_2^2}{I_2}$.
Magnet A :—	$t_1 =$	
Magnet B :—	$t_2 =$	

44. Determination of the Horizontal Intensity of the Earth's Field

Since the value of $\frac{M}{H}$ and of MH can be determined (see §§ 42 and 43 respectively) for any given magnet, we can use these results in order to determine the value of H, since $MH \Big/ \frac{M}{H} = H^2$.

Hence $$H = \sqrt{\frac{4\pi^2 I}{t^2} \times \frac{2d}{(d^2 - l^2)^2 \tan a}}.$$

(i.) Use the numerical results obtained in §§ 42 and 43 for the value of $\frac{M}{H}$ and MH, and calculate the value of H. Make

this calculation from the results obtained with both magnets (A and B), and thus obtain two independent values for H.

45. The Effect of a Rise of Temperature on the Moment of a Magnet

Apparatus required.—Large evaporating basin containing some heavy oil (*e.g.* linseed oil). Tripod and gauze. Centigrade thermometer. Wooden clamp. Short bar-magnet, or a piece of strongly magnetised knitting-needle. Magnetometer. Squared paper.

(i.) Place the magnetometer with its arms north and south, and raise it until the needle is at the same horizontal level as the magnet, which is contained in the dish of oil supported on the tripod immediately to the east of the magnetometer needle. Support the magnet so that its axis lies east and west. Clamp the thermometer so that its bulb is immersed in the oil. Take a series of simultaneous readings of the deflection and the temperature, both when the oil is being heated and when it is cooling. Tabulate your results in the following manner:—

Temperature.	Deflection (a.)	Tan a.

Plot these observations on squared paper, taking the temperatures as abscissae, and tangents of the angle of deflection as ordinates.

*46. Accurate Method of Determining H

Apparatus required.—Mirror magnetometer (see note 9, p. 219). Lamp and scale. Apparatus for determining time of vibration (see note 8, p. 218). Magnetised knitting-needle.

In observing deflections by means of a reflected beam of

light, it is necessary to remember that the reflected beam moves through an angle which is twice as great as that through which the mirror moves. If L (Fig. 34) represents the lamp and M_1 the mirror, suspended from O, then OS_1 will be the direction of the reflected beam. If the mirror is now deflected through an angle α (represented in the diagram by the angle S_1On, through which the normal to the mirror

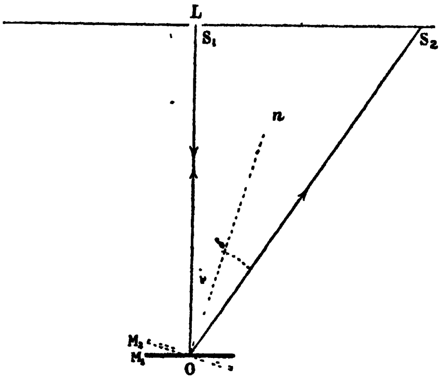


FIG. 34.—To illustrate that the angle through which a reflected beam is turned is twice that through which the mirror is turned.

moves), then OS_2 will be the direction of the reflected beam, and the angle (δ) through which the beam moves $= 2\alpha$.

By measuring the distances S_1S_2 and S_1O the angle δ can be calculated, since $\tan\delta = \frac{S_1S_2}{S_1O}$. For small angles, if $\delta = 2\alpha$, we may, with sufficient accuracy, say that $\tan\delta = 2\tan\alpha$.

Hence, $\tan\alpha = \frac{\tan\delta}{2} = \frac{S_1S_2}{2S_1O}$,

or, the tangent of the angle of deflection $=$

$$\frac{\text{deflection in cms.}}{2 \times \text{distance of mirror from cross wire.}}$$

(i.) Determination of $\frac{M}{H}$.—Adjust the magnetometer so that its face coincides with the magnetic meridian, and level

the instrument so as to allow the mirror to swing freely. Set up the galvanometer scale in the meridian and about 75 cms. distant from the mirror, and adjust its position so that the reflected beam of light coincides with the zero of the scale. Focus the cross wire on to the scale by means of the lens. Carefully measure the distance of the scale from the mirror, and also the length of the magnet.

Fix the magnet in the cork and carefully adjust it in a horizontal position, so that its axis is in the meridian and in line with the centre of the mirror. Note the distance of the near end of the magnet from the centre of the mirror, and add to this one half the length of the magnet (this will be the distance of the *middle* of the magnet from the mirror). Make another observation, with the magnet nearer to the mirror. Enter your results thus:—

Determination of $\frac{M}{H}$:—

Distance of scale from mirror (D) =
Length of magnet ($2l$) =
Distance of near end of magnet from mirror (d) = (i.)
" " " = (ii.)

$(d+l)$.	Deflection in cms. (s).	$\tan a \left(= \frac{s}{2D}\right)$.	a.
(i.)			
(ii.)			

rom (i.), $\frac{M}{H} = \frac{(d+l)^3}{} \tan a =$

(ii.), " "

Determination of MH.—Determine the time of one complete oscillation of the magnet by the method described in § 43. If a watch with small seconds' hand only is available, count sufficient oscillations to occupy at least 4 or 5 minutes. Carefully measure the length, diameter, and weight of the magnet. Enter your results thus:—

Time of one complete oscillation (t) =
Length of magnet ($2l$) =
Radius ,, (r) =
Weight ,, (w) =

$$\text{Moment of Inertia (I)} = \left(\frac{\overline{2l}|^2}{12} + \frac{\overline{r}|^2}{4}\right) \times w =$$

$$\text{MH} = \frac{4\pi^2 \text{I}}{t^2} =$$

Calculation of H :—

$$\text{MH} \Big/ \frac{\text{M}}{\text{H}} = \text{H}^2 =$$

Therefore H =

Additional Exercises

1. In a given position the horizontal intensity of the earth's field = 0·18, and the dip = 60°. Find the total intensity of the earth's field (cosine 60° = 0·5).

2. A compass-needle makes 50 oscillations per minute at a place where the dip is 60°, and 48 oscillations per minute at another place where the dip is 70°. Compare the total magnetic forces at the two places.

3. At Cape Town the total magnetic intensity is 0·36, and the dip is 56°; at London the total intensity is 0·47 and the dip 67°. If a magnet vibrating horizontally at London makes 16 oscillations in a minute, how many oscillations will it make in the same time at Cape Town? (cosine 67° = 0·39, cosine 56° = 0·56).

4. A short bar-magnet is placed on a table with its axis perpendicular to the magnetic meridian, and passing through the centre of a compass-needle. In London the compass-needle is deflected through a certain angle when the centre of the magnet is 25 inches from the centre of the needle. If the experiment be repeated in Bombay the magnet must be moved 5 inches nearer to the needle to produce the same deflection. Use these data to compare the horizontal forces in London and Bombay. (1895.)

5. Select two pieces of steel knitting-needle of equal length. Magnetise one of the pieces by stroking it 6 times with the pole of a bar-magnet, and magnetise the other by stroking it 12 times. Compare the moments of the magnetised needles by the method of Expt. 42. Place the stronger magnet in boiling water for a few minutes, and again compare their moments.

PART II

STATICAL ELECTRICITY

CHAPTER X

ELECTRIFICATION BY FRICTION

47. Attraction and Repulsion

Apparatus required.—Silk cord suspension and wire stirrup (Fig. 35). Rods of vulcanite and glass (see note 10, p. 220). Fragments of paper. Long wooden lath. Round-bottomed flask and clamp. Silk and woollen rubbers. Piece of thin flannel and a clothes' brush. Drying oven (see note 11, p. 220).

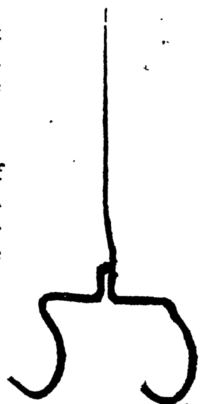


FIG. 35.—Stirrup for supporting electrified rods.

(i.) **Electrified Bodies attract Unelectrified Bodies.**—(*a*) Rub a rod of vulcanite on the coat sleeve (or with flannel), and hold the rod over small fragments of paper lying on the table. Notice how the fragments are attracted.

(*b*) Balance a long wooden lath on an inverted round-bottomed flask, and hold near to one end of it a rod of vulcanite which has been rubbed with dry flannel (or on the coat sleeve). Notice the attraction.

Repeat this experiment, but use a dry glass rod which has been rubbed with dry warm silk.

(ii.) **Unelectrified Bodies attract Electrified Bodies.**—(*a*) Suspend an electrified rod of vulcanite, and hold the hand near to it. Note how the vulcanite is attracted. Repeat this observation, with glass rubbed with silk.

(*b*) Rub a piece of dry warm flannel with a clothes' brush, and notice how it clings to the wall of the room.

(iii.) **Mutual Action between Electrified Bodies.**—(*a*) Suspend a rod of vulcanite which has previously been rubbed with flannel, and notice how it is repelled by another similarly electrified rod of vulcanite.

(*b*) Repeat the previous experiment, using two glass rods rubbed with silk. Notice the repulsion.

(*c*) Suspend an electrified rod of vulcanite, and hold near to it a rod of glass which has been rubbed with silk. Notice the attraction between the vulcanite and glass.

(*d*) Repeat Expt. 47 (iii. *c*), but previously heat the glass tube by holding it *in a Bunsen flame*, and rub it with silk while still hot. It will now be found to repel the electrified rod of vulcanite. If the glass rod is now allowed to cool completely, and then again warmed *in the drying oven*, it will be found to have recovered its property of attracting the electrified vulcanite.

It is usual to say *that the glass rod is + ly electrified, and the vulcanite − ly electrified.* The above experiments suggest the following rules:—(i.) *Bodies with like charges repel one another, and bodies with unlike charges attract one another.* (ii.) *A charged body always attracts an uncharged body.*

Expt. 47 (iii. *d*) indicates that glass becomes − ly electrified when rubbed with silk, if the glass has been previously heated in a Bunsen flame. The student should therefore carefully avoid warming the glass in this manner if a + ve electrification is desired.

48. Relation between the kind of Electrification and the kind of Rubber

Apparatus required.—Vulcanite and glass rods. Flannel and fur rubbers. Suspension.

(ii.) Suspend an electrified rod of vulcanite. Bring near to it a rod of glass which has been rubbed with fur. Note the repulsion, indicating that the charge on the glass must be *negative*. It has already been observed, in Expt. 47 (iii.), that glass becomes + ly charged if rubbed with silk.

49. The Pith-ball Electroscope

Apparatus required.—Pith-ball electroscope (see note 12, p. 220). Rods of vulcanite and glass. Silk and flannel rubbers.

(i.) Hold a glass rod, previously rubbed with silk, near to the pith-ball. Notice the attraction of the ball. If allowed to come into contact with the glass, the ball is afterwards repelled owing to the fact that it has acquired a + ve charge from the glass. The ball is now said to be + ly charged.

(ii.) Repeat the previous experiment with vulcanite, rubbed with flannel. After contact with the vulcanite, the ball is said to be − ly charged.

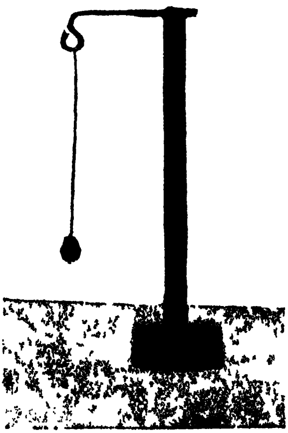


FIG. 36.—Pith-ball electroscope.

50. Conductors and Insulators

Apparatus required.—Pith-ball electroscope (Fig. 36). Vulcanite and flannel rubber. Metal wire. A Bunsen burner (or wax match). Strip of paper. Glass rod. Cotton and silk thread. Charcoal. Paraffin-wax. Oil, &c.

(i.) Rub a piece of vulcanite with flannel. Bring it near to the pith-ball. The ball is attracted, and after rolling about slightly over the surface of the vulcanite acquires a charge of the same kind and is consequently repelled. Touch the thick copper wire with the finger. The ball is at once

attracted again by the vulcanite, showing that the charge on the ball has escaped through the finger.

(ii.) Repeat the experiment, but touching the thick wire with a strip of paper instead of with the finger. The repulsion slowly diminishes, and the pith-ball is finally attracted once more. This shows that the charge has *slowly* escaped through the paper.

(iii.) Repeat the experiment, using *dry* glass instead of paper. The repulsion remains unaltered, showing that the glass is a non-conductor (*i.e.* an insulator).

Repeat the experiment with the following substances:—The flame of a Bunsen burner. Any metal wire, cotton thread, charcoal, wood, stone, wet glass, dry silk thread, wet silk thread, sulphur, shellac, wool, paraffin-wax, silk thread dipped in oil, ebonite, etc. etc.

Classify your results in the following manner:—

Conductors	Partial Conductors	Insulators

N.B.—Carefully notice that anything having moisture on its surface is a conductor, and that it is therefore essential to keep all the apparatus thoroughly dry.

51. Electrification of Conductors by Rubbing

Apparatus required.—Pith-ball electroscope. Rod of vulcanite. Brass tube, or sheet of zinc, fastened on an insulating handle (Fig. 37). Fur.

(i.) Hold the brass tube so that a finger is touching the metal. Flick the tube with the fur, and then hold the tube near to the pith-ball. Notice that there is no attraction.

If any charge is acquired it is just as rapidly conveyed away along the metal (which is a *conductor*) through the hand.

(ii) Charge the pith-ball – ly Hold the brass tube by its insulating handle, and flick the metal with the fur Hold the tube near to the pith-ball, and notice the repulsion.

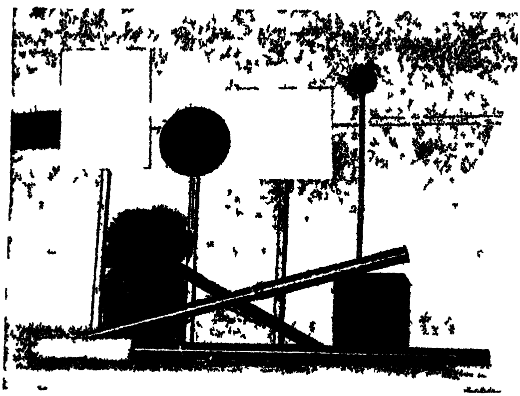


Fig 37.—Apparatus for electrostatic experiments

By adopting similar precautions we can show that all substances may become electrified when rubbed with suitable material

52. Simultaneous Production of Both Kinds of Electrification

Apparatus required—Pith ball electroscope Small square of glass and a piece of fur, both mounted on insulating handles (Fig 37) Ebonite rod, flannel cap and silk thread attached

(i) **Equal and Opposite Charges.**—Holding the glass and the fur by the handles, rub them together Keeping them in contact, bring them near to an uncharged pith ball No effect is seen When the fur is removed, the glass alone attracts the pith ball The fur alone also attracts it Evidently both the glass and the fur are charged, but since they have no effect when together, the charge on the fur must be equal and opposite to the negative charge on the glass To verify that the fur is positively charged, bring it near to a pith-ball charged positively and notice the repulsion

(ii.) **Another Method.**—Another method of proving the same result is to place a loose-fitting flannel cap, which is attached to one end of a long silk thread, over the end of an ebonite rod. Twist the thread round the cap and pull the thread so as to make the cap rotate round the end of the rod. As long as the cap remains on the rod no electrification can be detected. If the cap is removed (without touching it with the hand, but carefully supporting it by means of the silk thread) both will be found to be electrified.

53. Frictional Order

Apparatus required.—Two pith-ball electroscopes. Vulcanite, glass, silk, fur, metals, etc.

N.B.—In these experiments carefully remember, when using a pith-ball electroscope, that *repulsion* is the only sure sign that a body, held near to it, is charged. Hence it is advantageous to have two electroscopes, one charged +ly and the other −ly.

(i.) Rub various pairs of the substances named below together, and determine in each case which is +ly and which is −ly charged. Carefully tabulate these substances, so that any one of them will be charged +ly when rubbed with one lower on the list, but −ly when rubbed with one higher on the list. (Vulcanite, silk, paper, flannel, metals, ebonite, shellac, glass, sulphur, etc.)

Additional Exercises

1. A pith-ball is suspended from a metal stand by a fine thread. If you have a strongly-electrified glass rod, how can you find out whether the thread is a conductor or non-conductor of electricity?

2. A metal cup is placed on the plate of a gold-leaf electroscope which is then charged. Separate drops of water are allowed to fall into it from a metal saucepan held in the hand. No effect is produced on the leaves, but when the falling

water becomes a continuous stream, the electroscope is at once discharged. Explain these facts. (1894.)

3. Two persons stand on insulating stools, and one strikes the other several times with a piece of catskin. If a hand of each individual are brought near together a small spark is observed. Explain this.

CHAPTER XI

FIELDS OF FORCE. POTENTIAL

54. Electric Fields of Force

Apparatus required.—As shown in Figs. 38 or 39 (see note 13, p. 220). Vulcanite. Two metal spheres (or wooden spheres coated with tinfoil or black-lead), each on an insulating stand. Wimshurst machine. Copper wire.

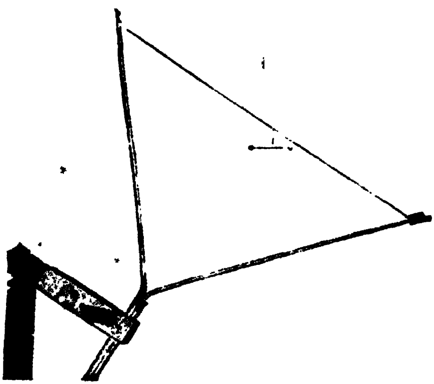


FIG. 38.—Apparatus for mapping electric fields of force.

The mutual forces of attraction and repulsion observed between various charged bodies closely resemble the forces between magnetic poles. This similarity suggests that electrified bodies may be surrounded by an *electric* field of force, at any point of which an *electric* force will be acting in a definite direction. This direction may be indicated by a *line of electric force*, just as the direction of the forces in a magnetic field are indicated by magnetic lines of force.

The methods of mapping out an electric field of force are far less satisfactory than in the case of a magnetic field.

The appliances shown in Figs. 38 and 39 are used for the purpose.

(i.) **Electric Field near a Charged Rod.**—Charge a rod of vulcanite, and hold the paper strip near to it. Observe the direction in which the paper points when it is held near to various points of the vulcanite. Sketch the rod, and show by dotted lines the direction in which the paper points, when held in the various positions.

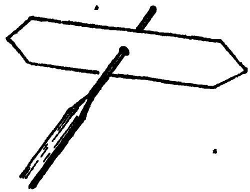


FIG. 39.

(ii.) **Near a Charged Sphere.**—Charge one of the spheres by connecting it, by means of a wire, to one terminal of a Wimshurst machine, the other terminal of which is similarly connected to the nearest gas-pipe. Observe how the lines of force radiate outwards from the sphere's surface (Fig. 40).

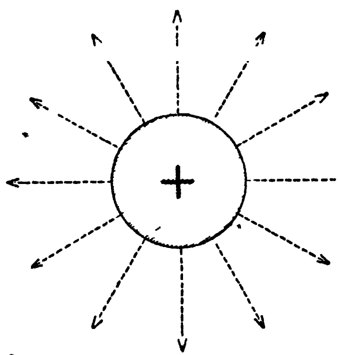


FIG. 40.—Lines of force due to a positively-charged sphere.

(iii.) **Between Oppositely-charged Spheres.**—Place two insulated metal spheres about 50 cms. apart, and charge them *oppositely* by connecting them to the poles of a Wimshurst machine. Verify the general distribution of the lines of force as shown by dotted lines in Fig. 41. Make a simple sketch of this in your note-book.

(iv.) **Between Similarly-charged Spheres.**—Connect the two spheres to the *same* pole of the Wimshurst machine, so as to give them *like* electric charges. Connect the other pole of the Wimshurst machine to the nearest gas- or water-pipe. Verify the distribution of the lines of force shown in Fig. 42. Make a simple sketch of this in your note-book.

An Electric Field may therefore be regarded as consisting

of *electric lines of force*, in the same way that we regard a

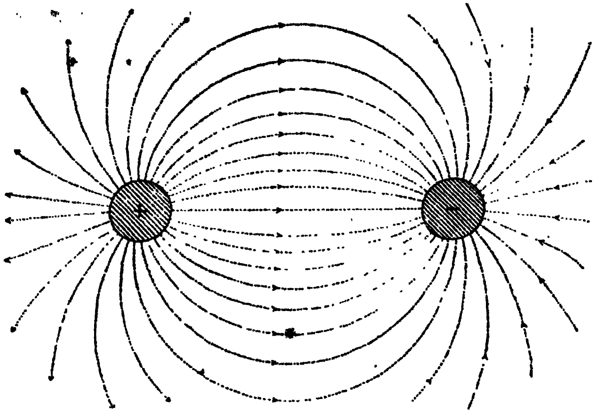


FIG. 41.—Lines of force due to two oppositely-charged spheres.

magnetic field as consisting of magnetic lines of force. To these electric lines of force we attribute properties similar to

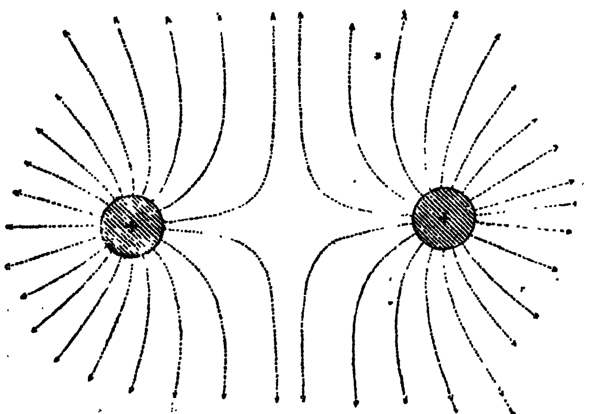


FIG. 42.—Lines of force due to two positively-charged spheres.

those possessed by stretched elastic threads (viz. a tendency

to contract lengthwise and to expand crosswise). In this manner it is possible to obtain a clear mental conception of the mutual attractions, or repulsions, between electrified bodies.

The *direction* of the force in a magnetic field is arbitrarily chosen as that in which a single *north-seeking* pole would tend to move. *In an electric field of force the direction of the force is arbitrarily chosen as that in which a + ly charged body tends to move.* Hence the lines of electric force may be regarded as running *from* a + ly charged body *towards* a − ly charged body.

55. Electric Potential

Work has to be done on any small + ly charged body in order to move it in the opposite direction to that in which it tends to move, and its *Potential Energy* (or, energy due to its position) will be thereby increased; in other words, the + ly charged body would be conveyed from a point of *lower potential* to a point of *higher potential*, but, if free to move of its own accord, it will travel from a point of higher potential to a point of lower potential.

If, therefore, the space surrounding any + ly charged body is considered, it will be understood from the above reasoning that the potential is greater at points near to the charged body than at more distant points. But, in the space surrounding any − ly charged body, the potential is greater at more distant points than at points near to the body; at a great distance the potential is *zero*, hence the potential nearer to the charged body will have a − ve value, and the potential will become more and more − ve as we approach the − ly charged body.

If the space between two oppositely charged bodies (*e.g.* Expt. 54, iii.) is considered, it will be understood that a small + ly charged sphere, which is free to move, and situated near to the + ly charged body, will travel *from* the + ly charged body *to* the − ly charged body; in other words, it will travel from points of higher to points of lower potential.

No electric forces originate from uncharged bodies, hence the region round them (in the absence of any charged

bodies) will be one of zero electric potential. An uncharged body has zero potential, and since the earth may be regarded as a huge spherical conductor which is uncharged, it is usual in experimental work to take the potential of the earth as our zero or starting-point for measurement (In the same way gravitational potential is measured from sea level)

The relative potential at various points in a field of electric force may be represented graphically in the manner shown in Fig 43 The lengths of the vertical lines indicate the

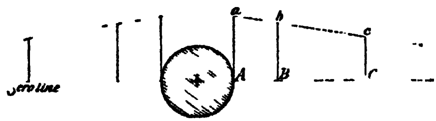


Fig 43 —Potential diagram

relative magnitudes of the potential at the various points A, B, and C, lines drawn *above* the zero line indicate *positive* potential, and lines drawn *below* the zero line indicate *negative* potential

(i) Sketch the potential diagram for two spheres of equal size and charged with equal and *opposite* charges, and placed a short distance apart

(ii) Sketch the potential diagram for two spheres of equal size and charged with equal and *similar* charges, and placed a short distance apart

56. Flow of Electricity

In the previous section we have imagined the small +ly charged sphere to be movable Supposing, now, that this small charged sphere is fixed in position, and that a mass of conducting material is brought into contact with the small sphere, then the *charge* will be transferred along the conducting material if, by so doing, it can move into a region of lower potential. *Electricity tends to flow from points of higher potential to points of lower potential*, and will do so if the various points are connected by means of conducting material

Moreover, the flow will continue along any conductor

until the potential is the same at all points; in fact, if any conducting body is placed in an electric field of force, the electricity on its surface will redistribute itself in such a manner as to make the potential the same at all points

This theoretical reasoning will find application in the experiments described in the following chapter.

ADDITIONAL EXERCISES

1 Make a pencil sketch indicating a few equipotential lines between two oppositely charged spheres Describe the potential changes along the line joining the centres of the spheres

2 Spheres of equal size are placed a short distance apart, and charged with unlike charges, the + ve charge on one being twice as great as the − ve charge on the other Divide the zero line between the surfaces of the two spheres into six equal parts, and state in words the potential changes along this line as you proceed from the one sphere to the other.

CHAPTER XII

ELECTROSTATIC INDUCTION

57. Preliminary Experiments with a Gold-leaf Electroscope

Apparatus required.—Gold-leaf electroscope (see note 14, p. 221). Proof plane. Glass rod, and silk rubber. Vulcanite rod, and fur rubber.

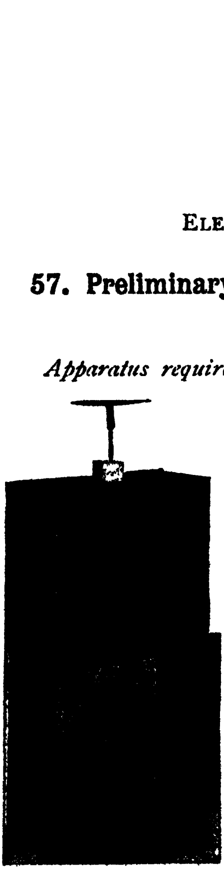


FIG. 14.
Gold-leaf electroscope.

(i.) Electrify the glass rod by rubbing it with silk, and lightly rub the proof plane over the surface of the glass so that it may acquire a slight charge from the glass. Touch the disc of the electroscope with the proof plane. The instrument is now +ly charged. Notice the divergence of the leaves.

(ii.) Hold the charged glass rod above the disc of the electroscope, and observe the *increased* divergence.

(iii.) Electrify the vulcanite rod by rubbing it with fur. Hold the vulcanite over (but not too near to) the disc of the electroscope. Observe the *diminished* divergence.

(iv.) Hold the hand just above the disc. Again observe the *diminished* divergence.

(v.) Discharge the electroscope by touching the disc with the finger, and charge it – ly by means of the vulcanite and proof plane (in the same manner as described in Expt. 57, i.).

FIG. 45.—Proof plane.

(vi.) Hold the charged glass rod above (but not too near to) the disc of the electroscope. Observe the *diminished* divergence.

(vii.) Hold the charged vulcanite rod above the disc. Observe the *increased* divergence.

(viii.) Hold the hand just above the disc. Again observe the *diminished* divergence.

From these simple experiments we obtain the following rules :—

An Increased Divergence indicates *a similar charge.*

A Diminished Divergence indicates either *an unlike charge* or an earth-connected conductor.

The latter rule shows that an *increased* divergence is the only sure test of *electrification.*

58. Electrostatic Induction

Apparatus required.—A wooden cylinder (coated with tin-foil or with black-lead) supported on an insulating stand. Glass and vulcanite rods. Silk and fur rubbers. Gold-leaf electroscope.* Proof plane (see note 15, p. 221). Two metal knobs, on insulating stands.

(i.) **Induced Charges.**—Charge the electroscope – ly (by Expt. 57, v.). Hold a charged glass rod near to one end (A) of the wooden cylinder (coated with tinfoil, Fig. 46), and touch A with the proof plane. Hold the proof plane over the disc of

* If sufficient instruments are available, it is convenient for the student to have two electroscopes—one charged + ly, the other – ly.

the electroscope, and observe the increased divergence, thus showing that the proof plane has acquired a − ve charge.

Still holding the glass rod in position, test the other end (B) in the same manner, and observe that the proof plane has acquired a + ve charge. In order to strictly verify this, charge the electroscope + ly (by Expt. 57, i.) and repeat the observation.

The temporary charges at A and B are caused by electrostatic induction due to the charged glass rod.

The upper portion of Fig. 46 represents the distribution of the lines of force in the experiment, and the potential diagram through the axis of the cylinder is shown in the lower portion of the same figure. The end A is nearer than B to the glass rod, and is consequently at a higher potential. The cylinder is a conductor, therefore electricity flows from A towards B, and the flow will continue until the potential of the cylinder is uniform. Lines of electric force proceed from the + ve charge on the glass rod to the − ve charge on A; lines of force also proceed from the + ve charge at B towards the walls of the room. *Notice how the lines of force appear to converge towards A, and to diverge outwards from B, and how this suggests the idea that the cylinder is a better conductor than the surrounding air for the lines of force.*

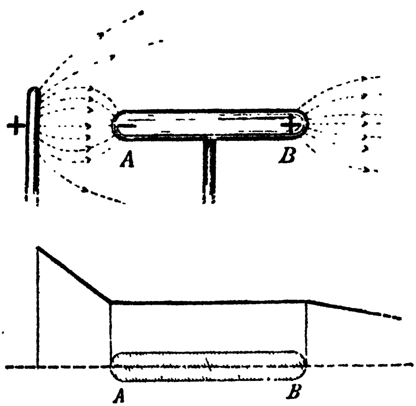


FIG. 46.—Potential diagram of an insulated cylinder charged inductively.

Remove the glass rod to a distance, and verify that the cylinder is now uncharged.

(ii.) **Bound and Free Charges.**—Again hold the charged

glass rod near to A, and momentarily touch the cylinder with the finger. Without moving the glass rod, test the ends A and B, and prove that A is charged – ly, and that B is uncharged.

When the cylinder is touched it becomes connected to *the earth by means of a conductor, which enables electricity* to pass until the potential of the cylinder is the same as that of the earth, viz. *zero.* Notice that, although the potential of the cylinder is zero, the end A has a – ve charge, which would be expected in ordinary circumstances to give a – ve potential to the cylinder. But it must be remembered that the nearness of the charged glass rod tends to give the cylinder a + ve potential. These two effects are equal and opposite, thus giving to the cylinder an apparent zero-potential.

Draw a diagram (similar to Fig. 46) showing where lines of force are found, and also draw a potential diagram for the line along the axis of the cylinder.

(iii.) **A Conductor charged – ly by Induction.**—Remove the glass rod, and, without touching the cylinder with the finger, prove that there is a – ve charge distributed over the entire surface. *The cylinder has been charged – ly by induction.*

The potential of the cylinder is now, of course, uniformly – ve.

Draw a diagram (similar to Fig. 46) showing the *direction* of the lines of force, and also a potential diagram for the line along the axis of the cylinder.

(iv.) **A Conductor charged + ly by Induction.**—Repeat Expts. 58 (i.-iii.), but use a vulcanite rod instead of the glass rod. Verify that, in 58 (i.), A is + ly charged, and B – ly charged; that, in 58 (ii.), A is + ly charged, and B uncharged; and that, in 58 (iii.), the cylinder has been + ly charged by induction.

In each case draw the same diagrams as required in the experiments with the glass rod, and briefly explain each diagram.

(v.) **Separation of Induced Charges.**—Verify the result obtained in Expt. 58 (i.) in the following manner:—Place two insulated metal knobs in contact with each other, and bring an

electrified glass rod near to one of them (Fig. 47). Keeping the rod in position, now remove the more distant sphere, and

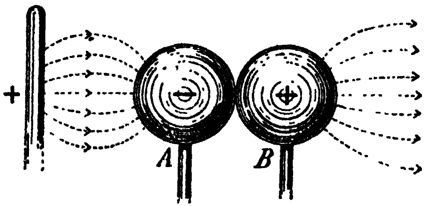


FIG. 47.—To illustrate Expt. v.

test the charges on both spheres. A is – ly and B is + ly charged. While in contact they act as one conductor, and the charge on the glass rod acts upon them as if such were the case.

59. Theory of the Gold-leaf Electroscope

Apparatus required.—Gold-leaf electroscope. Rods of glass and vulcanite. Silk and fur rubbers. Insulating stand (see note 16, p. 222).

(i.) **The Electroscope charged + ly by Induction.**—(*a*) Rub a vulcanite rod with fur, and hold the rod over the disc. Notice how the leaves diverge. Fig. 48 indicates how the lines of force are distributed. Bear in mind that the vulcanite is – ly charged, and that the direction of the lines of force will consequently be *towards* the vulcanite.

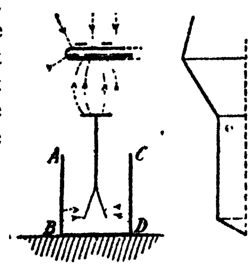


FIG. 48.

AB and CD (Fig. 48) represent the strips of tinfoil on the inner surface of the glass, and BD is the disc of foil on the base board. ABCD is earth-connected through the table on which the instrument stands, and therefore has a *constant zero potential.*

Fig. 48 also includes a potential diagram for this case; the diagram indicates the changes of potential along a line

coinciding with the axis of the electroscope. The vertical dotted line is taken as the line of zero potential. Positive potentials are represented by horizontal lines drawn to the *right* of the zero line, and negative potentials by lines drawn to the left. The thick continuous line represents the changes in potential along the line of the electroscope's axis.

The gold leaves are farther from the vulcanite than the disc, and they are therefore in a region of higher potential; this difference of potential causes a redistribution of electricity resulting in a – ve charge in the leaves and a + ve charge in the disc (see § 58, i.). This distribution gives a *uniform* potential to the disc and leaves; but, remember, this uniform potential will be *negative* (not *zero*), because the instrument is in a field of negative potential.

ABCD is earth-connected, and therefore at zero potential. Lines of force will pass from ABCD to the leaves, because the leaves are at a lower potential than ABCD; owing to the tendency of the lines of force to shorten, the leaves will be pulled apart. The same number of lines of force will pass from the disc to the vulcanite.

(*b*) Now touch the disc with the finger, and notice how the leaves fall together.

By touching the disc, the potential of the disc and leaves is raised to zero (the same as ABCD), therefore no lines of force will pass between ABCD and the leaves. The potential difference between the disc and the vulcanite is now greater than it was before, and this will cause more lines of force to pass between the two.

Make a diagram in your note-book (similar to Fig. 48), indicating how the lines of force are distributed and how the potential changes along a line coinciding with the axis of the electroscope.

(*c*) Remove the vulcanite to a distance. Notice how the leaves diverge.

The + ve charge, formerly distributed over the disc, has now distributed itself uniformly over the disc and leaves. The instrument is now no longer in a region of – ve potential, because the vulcanite has been removed, and the potential of the instrument is now only due to its own

charge; its potential is therefore + ve. Since the leaves are at a higher potential than ABCD, lines of force will pass *from* the leaves *to* ABCD, and the leaves will therefore diverge.

Make a sketch and potential diagram as before.

(ii.) **Effect of a Neighbouring + ve Charge.**—Without discharging the instrument, hold a + ly charged glass rod over the disc. Notice the increased divergence of the leaves.

The region near to the glass rod has + ve potential, and therefore the potential of the instrument has been increased. This will cause more lines of force to pass between the leaves and ABCD.

Make a sketch and potential diagram as before.

(iii.) **Effect of a Neighbouring − ve Charge.**—Hold a − ly charged rod of vulcanite some distance above the disc. Why is the divergence less? How has the potential of the instrument been altered? Make a sketch and potential diagram.

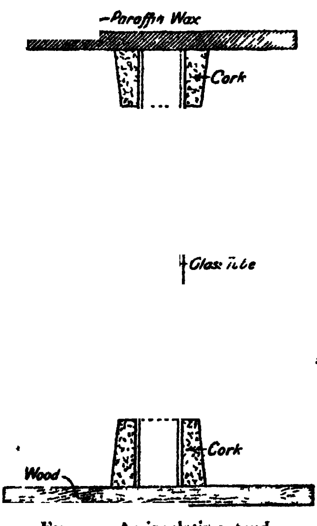


FIG. 49.—An insulating stand.

Bring the rod gradually nearer, and notice how the leaves finally collapse. Explain the reason for this with the aid of a sketch.

Bring the rod still nearer to the disc, and explain why the leaves again diverge.

If you hold your hand just above the disc, you will notice that the leaves partially collapse. Explain the reason for this.

(iv.) **The Electroscope Charged − ly.**—Repeat Expts. i.-iii., but use glass rod instead of vulcanite, and *vice versâ*. Give explanations, as before, for all the observations made.

(v.) **The Electroscope placed on an Insulating Stand.**—Place the uncharged electroscope on an insulating stand. Connect the disc to the tinfoil

base by means of a thin wire. Hold a charged body near to the instrument, and observe that the leaves do not diverge.

The leaves and the tinfoil are at the same potential, and therefore no lines of force pass between them to cause a divergence.

Remove the thin wire, and observe that a charged body near to the instrument will cause a divergence of the leaves. If the charged body is an electrified glass rod, the potential of the leaves and of the tinfoil will be raised, but not to the same degree; hence there will be a potential difference causing a divergence of the leaves.

Touch the tinfoil with the finger, so as to reduce its potential to zero. The potential difference is now greater, and this is shown by the increased divergence.

From these results we see that the divergence of the leaves depends upon the potential difference between the leaves and the earth-connected tinfoil; if the instrument is + ly charged, a *rise* in the potential of the leaves will produce an *increased* divergence; a *fall* in potential will produce a *reduced* divergence. The electroscope may therefore be used as a means of detecting any changes in potential in the surrounding space.

60. The Electrophorus

Apparatus required.—Electrophorus (see note 17, p. 222). Fur rubber. Gold-leaf electroscope. Vulcanite rod. Bunsen burner or spirit-lamp.

(i.) **Charging an Electrophorus.**—Charge the vulcanite − ly by rubbing with fur or flannel. Place the metal disc resting on the top of the vulcanite. Touch the disc. Raise the disc away from the vulcanite. Test the charge on the disc by holding it over the disc of a + ly charged gold-leaf electroscope; an increased divergence shows that the electrophorus disc is + ly charged.

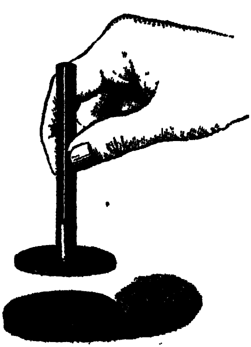


FIG. 50.—An electrophorus.

Bring the finger near to the disc; when sufficiently near, a small spark is seen to pass from the disc to the hand. Completely discharge the disc by touching it with the hand. Again place it on the vulcanite, and repeat the experiment. The disc may be charged many times without it being necessary to re-charge the vulcanite.

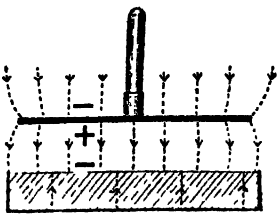


FIG. 51.—The field of force due to an electrophorus.

(ii.) **The Induced Charges in an Electrophorus.** — Completely discharge the electrophorus by passing it through the flame of a Bunsen burner. Place the electrophorus on the disc of the electroscope, and flick it with fur. Note the divergence of the leaves, and explain the reason for this. Test the charge present in the leaves by holding a −ly charged rod of vulcanite over the disc. Place the disc of the electrophorus in position, and touch its upper surface with the finger. What result do you observe? Explain it in a few words.

61. Electrical Screening

Apparatus required.—Electrophorus. Proof plane. Gold-leaf electroscope. Cylindrical jacket of metal gauze (large enough to completely cover the electroscope). Sheet of metal, with an insulating handle attached. Vulcanite rod and fur rubber. Wax taper.

(i.) **The Walls of a Room serve as an Electrical Screen.** —Hold the charged electrophorus disc 3 or 4 cms. away from the wall of the room. Touch with a proof plane the surface of the wall which is within the shadow of the disc. Bring the proof plane over the disc of a −ly charged electroscope. How is the proof plane charged? Remove the electrophorus disc, and again test the same portion of the wall. Is the proof plane again charged? Are the walls of the room conducting or non-conducting?

Repeat the experiment, holding the disc just above the table. The same results are obtained.

Hence we may regard the room as an earth-connected

conductor, and therefore always at zero potential. Whatever experiments may be in progress, the lines of force will be restricted to the space within the room, and it will be impossible to detect any electrical forces beyond the boundaries. *The walls, etc., of the room may be said to serve as an electrical screen, protecting the outer region from all electrical forces which may exist within the room.* Similarly, the space within the room will be electrically screened from all forces which may exist outside the room. These results may be verified in the following manner :—

(ii.) **Methods of Screening an Electroscope.**—(*a*) Place the gauze jacket over the electroscope, and stand it on the table ; the gauze is earth-connected, and therefore analogous to the walls of the room. Hold the charged electrophorus disc near to the gauze. Is the electroscope screened?

(*b*) Remove the jacket, invert it, and place it on a stand (non-insulating) as near as possible to the disc of the electroscope. Hold an electrified rod of vulcanite inside the jacket (without touching the gauze). Is the electroscope screened ?

(*c*) Hold the vulcanite just over the disc of the electroscope. Observe the divergence. Now place a large sheet of metal, earth-connected by holding it in the hand, between the wax and the disc (*and touching neither*). Do the leaves still diverge ? Is the plate *screening* the electroscope ?

(*d*) Support the metal plate by means of its insulating handle, and repeat Expt. 61 (*c*). Notice that the electroscope is no longer screened.

(iii.) Hold a burning taper a few inches away from the disc of the charged electroscope. Notice how quickly the instrument is discharged. Re-charge the electroscope, and hold an earth-connected sheet of metal between the disc and the flame. Is the instrument again discharged? or, is it screened by the plate?

62. Equality of Potential at all Points of a Charged Conductor

Apparatus required.—Wooden cylinder (coated with foil or black-lead). Insulating stand. Proof plane. Thin copper wire. Gold-leaf electroscope.

(i.) **Equality of Potential when Charged.**—Charge the insulated cylinder by means of the electrophorus. Connect the disc of a proof plane to the disc of a gold-leaf electroscope by means of a thin copper wire. Holding the proof plane by its insulating handle, bring it into contact with the cylinder, and observe the divergence produced (Fig. 52).

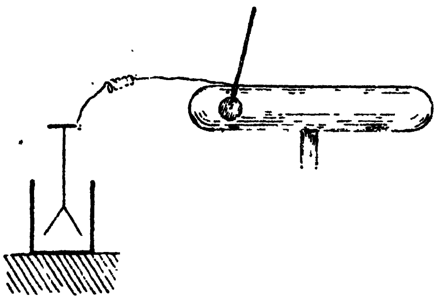


FIG. 52.

The degree of divergence is a measure of the potential of the point on the cylinder which is in contact with the proof plane. Move the proof plane to other points of the cylinder. Does the divergence remain unaltered? Is the potential the same at all points?

(ii.) **Equality of Potential when in a Field of Force.**—Discharge the cylinder, and hold the charged electrophorus disc near to one end. Again test whether the potential of the cylinder is uniform.

63. Seat of the Charge on a Conductor

Apparatus required.—Hollow tin. Insulating stand. Electrophorus. Proof plane. Electroscope.

(i.) Place a coffee-tin (or calorimeter) on an insulating stand. Charge the tin by means of the electrophorus. Touch the outside of the tin with a proof plane, and verify the nature of the charge with a gold-leaf electroscope. Discharge the proof plane, and with it touch the inside of the tin; carefully remove the proof plane without touching the edge or outer surface of the tin. Test it by means of the electroscope. Is the proof plane still charged? or, is the charge distributed solely over the *outer* surface of the conductor?

64. Induced Charge on the Inner Surface of a Hollow Conductor

Apparatus required.—Hollow can. Insulating stand. Metal sphere,* with insulating handle. Electrophorus. Proof plane. Electroscope (two electroscopes are convenient). Thin wire.

(i.) **Internal Induced Charges.**—Place the can on the table. Introduce the insulated sphere, which is charged + ly, well inside the can, taking care that the sphere does not touch the can. Touch the *inside* of the can with a proof plane, and withdraw it, being careful not to touch the sphere or the edge of the can. Test the charge on the proof plane by means of an electroscope. What charge do you find on the inside of the can?

With the sphere still in position, test the outside of the can, and verify that there is no charge present.

Make a diagram of the apparatus, indicating the lines of force which may be present. How does this experiment resemble Expt. 58 (i.)?

(ii.) **Faraday's Ice-pail Experiment.**—Place the can on an insulating stand, and connect the can to the disc of an electroscope by means of a thin wire. Introduce an insulated sphere (or foil-covered bottle), which is charged + ly, well inside the can, taking care not to touch the sides of the can. If the can is sufficiently deep, all the lines of force from the charged sphere are now intercepted by the sides of the can, on the inside of which an induced – ve charge is found. The induced + ve charge is distributed partly over the outer surface of the can and partly over the electroscope, from both of which there are lines of force proceeding to any neighbouring earth-connected conductors. Observe the divergence of the leaves. Allow the sphere to touch the inside of the can, thus making it a portion of the inside of the charged conductor. The divergence remains unaltered. Remove the sphere, and test whether it still has any charge. The sphere

* Instead of a sphere, a convenient carrier may be made by covering the outside of a 2 oz glass bottle with tinfoil, and fastening a rod of sealing-wax to the cork to serve as an insulating handle.

has no remaining charge, nor is there any charge on the inside of the now empty can.

The sphere's charge has been exactly neutralised by the induced – ve charge on the can, without leaving an excess of either (for had there been an excess of either it must have proceeded to the outside of the can, and so modified the divergence of the leaves). All the lines of force which originally proceeded from the sphere evidently disappeared when the sphere touched the can.

Hence, the total induced charge is equal and opposite to the inducing charge.

The induced + ve charge is equal to the induced – ve charge, hence the charge remaining on the can must be equal to the charge originally on the sphere. This explains the only method which is known for completely transferring the charge from one insulated conductor to another. The conductor which is intended to receive the charge must be hollow and of sufficient size to allow the charged conductor to be placed inside it. If the conductors only touch one another on the outside, then the charge will be *shared* between them, and will not be found on one conductor only.

(iii.) Using the same apparatus as in Expt. 64 (ii.), touch the *outside* of the tin with the charged sphere. Observe the divergence of the leaves. Lines of force proceed from both the sphere and the can. Test the charge still remaining on the sphere by bringing it near to the disc of another electroscope which is charged + ly. Now touch the *inside* of the can with the sphere. Notice the increased divergence, and verify that the sphere is now completely discharged.

65. Distribution of the Charge on the Surface of a Conductor

Apparatus required.—Tinfoil-coated sphere, cylinder, and pear-shaped conductor. Insulating stand. Proof plane. Electroscope. Hollow can. Insulated metal plate.

(i.) **On a Sphere.**—Charge the insulated sphere. Touch the surface with the flat side of a proof plane, and bring the proof plane into contact with the disc of an uncharged electroscope.

Notice the degree of divergence Discharge the proof plane and electroscope Test other portions of the sphere's surface in the same way Is the divergence the same in each case? Draw an outline of the conductor, and show by means of a dotted line, outside the conductor, how the charge is distributed (the distance of the dotted line from each portion of the surface indicating the magnitude of the charge found on that portion)

(ii) **On Pear-shaped Conductor.**—Repeat Expt 1 with the insulated pear shaped conductor, and make a diagram as before

(iii) **Hollow Can.**—Repeat Expt 1 with the hollow cans

(iv) **Metal Plate.**—Repeat Expt 1 with the metal plate

The quantity of electricity on each square centimetre of the surface of a conductor is not necessarily the same (This quantity is usually termed the *Density* of the charge)

Hence, although the potential of a charged conductor is uniform, the density is not necessarily so, but depends upon the shape of the conductor

ADDITIONAL EXERCISES

1 The total induced electric charge is equal to the charge that induces it Demonstrate this (Inter County Sch, L C C 1900)

2 How would you prove that two points may have the same potential, though one is charged with positive electricity, and the other is either uncharged or charged with negative electricity?

3 Inside a hollow spherical conductor (insulated) are placed two small spheres, insulated from each other and from the outer vessel, the one charged with positive and the other with a smaller charge of negative electricity. Draw a picture showing the distribution of the lines of electric force outside the conductor (1893)

4 An insulated conductor, A, is brought near to the cap of a gold leaf electroscope which has been charged positively State and explain what will happen, (1) if A is unelectrified, (2) if it is charged positively, (3) if it is charged negatively. (1887.)

5. Describe how to arrange an experiment so that a con-

ductor charged all over with negative electricity, may nevertheless receive a further charge of negative electricity on being connected with the ground by a conducting wire (1896)

6 Into an insulated uncharged metal jar standing on the cap of an electroscope an electrified brass ball is lowered without contact, the jar is then touched for a moment with the finger, and the ball is next allowed to touch the jar, after which it is removed Explain the various effects produced on the gold leaves (1898)

7. Four precisely similar insulated metal balls, A, B, C, D, are placed in a row The two inner balls (B and C) are in contact, and the distances AB and CD are equal If A and D are electrified, what will be the electrical states of B and C after first one and then the other has been removed from the neighbourhood of A and D, (1) when the charges on A and D are equal and opposite, (2) when the charges are equal and similar? (1892)

8 A pad of flannel is placed at the bottom of a metal vessel which is insulated and connected by a wire with the cap of a gold leaf electroscope One end of a long rod of sealing wax is now rubbed against the flannel What indications will the electroscope give, (1) while the rubbing is going on, (2) when the sealing wax is withdrawn? (1892)

9. An electrified body is brought into the neighbourhood of (*a*) an insulated conductor, (*b*) an earth connected conductor Describe exactly the effect on the potentials of the electrified body and of the unelectrified conductors in each case (1892)

10 Can the leaves of an electroscope be made to diverge when they are kept at zero potential? If so, describe how, and explain why (1895)

11 Two equal insulated conducting spheres A and B are placed at some distance apart and connected by a long thin wire They are then charged An uninsulated metal sphere C is brought near to A After this the wire and the sphere C are removed in turn Will the charges on A and B now be equal? Give reasons for your answer (1894)

12. Two insulated metal balls, of which one only is electrified, are placed near each other If an unelectrified plate of paraffin is introduced between them, how is the distribution of the electricity on the balls altered? (1888)

13. An electrophorus after being charged in the ordinary way, is placed on the cap of an electroscope. The metal cover is then placed on the electrophorus by means of its insulating handle, and, lastly, the cover is momentarily touched with the finger. Describe and give reasons for the behaviour of the gold leaves in each of these three cases. (1888.)

14. A gold-leaf electroscope is placed upon an insulated metal stand. State and explain the indication of the leaves when the stand receives a positive charge. How would the indication be modified if the leaves were earth-connected? (1898.)

15. Two similar deep metal jars are placed on the caps of two similar electroscopes at some distance apart and the caps are connected by a fine wire; a positively electrified ball is lowered into one of the jars without contact. Explain the effect as to potential and divergence on both sets of leaves, and also that which occurs on breaking the wire connection by means of a silk thread and then removing the ball without allowing it to touch the jar. (1898.)

CHAPTER XIII

CAPACITY. CONDENSERS. LEYDEN JARS

If two insulated conductors A and B are experimented with, and it is found that A requires a larger charge of electricity than B requires in order to raise its potential to the same degree, it is said that the *capacity* of A is greater than that of B. In other words, the capacity of a conductor is measured by the quantity of electricity which must be given to it in order to raise its potential to a given amount.

The capacities of different conductors may therefore be roughly compared by charging them to the same potential and afterwards comparing the quantities of electricity on each.

66. Relation between the Size of a Conductor and its Capacity

Apparatus required.—Two metal spheres, each with an insulating handle (instead of the spheres, bottles of different sizes may be used, coated on the outside with tinfoil, and having a rod of vulcanite fastened to the cork). Hollow can. Electroscope. Insulating stand. Electrophorus.

(i.) **When the Potential is the same.**—Place the can on the disc of the electroscope. Place the two spheres on the insulating stand and in contact with each other. Give a small charge to the spheres by means of the electrophorus. Are the spheres now at the same potential? Convey the larger sphere to the electroscope, lower it into the can, and allow it to touch the inner surface, thus transferring the entire charge to the can and electroscope. Withdraw the

sphere, and observe the divergence of the leaves. Discharge the electroscope. Proceed in the same manner with the smaller sphere, and observe whether the divergence is greater or less than before. Which sphere has the larger *capacity?*

(ii.) **When the Charge is the same.**—Place one of the spheres on the insulating stand, and connect it by means of a wire to the disc of the electroscope. Give a small charge to the sphere by means of the electrophorus, and notice the divergence of the leaves. Bring the other insulated sphere (uncharged) into contact with the charged sphere. Judging from the divergence in the leaves, what change in potential has taken place? Since the quantity of electricity has remained the same, what is the cause of the change in potential?

67. Dependence of the Capacity of a Conductor upon the presence of Neighbouring Conductors

Apparatus required.—Electroscope. Vulcanite and fur. Metal plate with insulating handle.

(i.) **An Earth-connected Conductor.**—Charge the electroscope, and observe the divergence of the leaves. Hold the hand just above the disc, and note how the divergence of the leaves is altered. What change is caused in the potential of the instrument? Has the capacity of the instrument been altered by holding the hand over it?

(ii.) **An Insulated Conductor.**—Hold an insulated metal plate just over the disc of the charged electroscope. Can you observe any change in the potential of the instrument? Now touch the plate with the finger, carefully watching the leaves, and notice any further change in the potential. Is the capacity of the instrument greatest before the metal plate is brought near, or when it is insulated and above the disc, or when it is earth-connected?

This apparent *condensing* of electricity on any charged conductor is the principle upon which so-called *condensers* depend.

A Condenser is defined as any arrangement by which the capacity of a conductor is artificially raised.

68. The Condenser

Apparatus required—A simple condenser (see note 18, p 222) (two condensers are necessary for Expt 68, ii) Electroscope Electrophorus and proof plane Thin copper wire Slab of paraffin wax Sheet of thick plate glass

(i) **Relation between Capacity and Thickness of Medium.**—Connect plate A to the electroscope by means of copper wire, and connect B to earth Give a small charge to A by

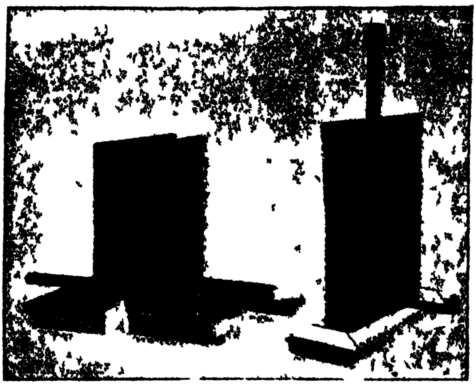


Fig 53 —A simple form of condenser (as used in the Elementary Physical Laboratory The Owens College Manchester)

means of the electrophorus and proof plane Observe the divergence of the leaves when B is about 20 cms distant from A. Slowly move B towards A, and observe the diminution of divergence Slowly remove B away from A, and observe the gradual increase of divergence The plates A and B constitute a simple form of condenser

Hence, *the capacity of a condenser is increased when the distance separating the conductors is diminished*

(ii.) **Relation between Capacity and Area of the Plates.**—Use two condensers, similar to that used in Expt 68 (i), and call them AB and A'B'. Connect A and A' to the same

electroscope, and connect B and B′ to earth, while the plates of the condensers are well separated, charge A and A′ sufficiently to produce a considerable divergence. Move B towards A, and note the diminution of divergence. Leave B in this position, and then move B′ towards A′, and note the further diminution.

The final effect is approximately the same as though a single condenser having plates of twice the size of AB had been used.

Hence, *the capacity of a condenser depends directly upon the area of surface of the two conductors.*

(iii.) **Capacity depends upon the Medium.**—Place B about 3 cms. from A (which is connected to the electroscope), and give a small charge to A. Notice the divergence. Carefully insert a square slab of paraffin-wax (about 1 cm. thick, and slightly larger in area than the plates) between A and B. Notice the diminution of divergence, and how it increases to its original value when the slab is removed.

Repeat this experiment, but use a slab of plate glass instead of the paraffin-wax.

Hence, *the capacity of a condenser depends largely upon the medium through which the lines of force pass.*

In these experiments the effects of replacing a portion of the air by paraffin-wax or glass is the same as if the conductors had been brought still nearer together. The wax and the glass seem to transmit the lines of force more readily than air. This varying power of transmitting the lines of electric force is termed the *Specific Inductive Capacity* (*S.I.C.*). The *S.I.C.* of glass is greater than that of wax, and that of wax is greater than that of air. Nearly all insulating solids have a higher *S.I.C.* than air.

69. Specific Inductive Capacity of Paraffin-wax

Apparatus required.—Condenser (see note 18, ii., p. 222). Gold-leaf electroscope. Slab of paraffin-wax (at least 3 cms. thick).

A and B (Fig. 55, I.) represent the two plates of a condenser; A is connected to a gold-leaf electroscope, and is charged

sufficiently to cause a slight divergence of the leaves; B is earth-connected. A slab of paraffin-wax is placed between A and B, but not touching either plate. The degree of divergence of the leaves, which can be observed by means of the circular scale behind the leaves, is a measure of the

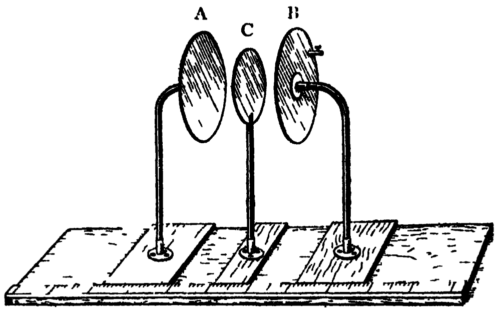


FIG. 54 —Another form of condenser.

potential to which A is raised. If the wax slab is removed the divergence *increases*, showing that the capacity of the condenser has been *diminished* by thus substituting air for wax. The original capacity can be restored by moving B slightly towards A (Fig. 55, II.), thus diminishing the width of air between the plates.

The width of air (equivalent in its inductive capacity to the wax)

$$= \text{width of paraffin-wax} - \text{distance through which B is moved.}$$

$$S.I.C. \text{ of paraffin-wax} = \frac{\text{Width of paraffin-wax}}{\text{Equivalent width of air}}.$$

(i.) Connect up the condenser and electroscope as shown in Fig. 55; if possible, remove the top-plate of the electroscope, and replace it by a binding-screw. Place the paraffin-wax in position between A and B. Earth-connect plate B by means of a wire, and give a slight charge to A. Place A and B so that the front edge of their supports slide against the graduated edge of a millimetre scale. Note the scale reading of plate B,

and also the divergence of the leaves. Quickly remove the paraffin-wax. Carefully move B towards A until the original divergence is restored, and note the scale reading of B. Measure the thickness of the wax slab.

It may happen that the surface of the wax slab will have acquired a slight charge either by touching the plates or by rubbing the fingers, in which case serious errors will be introduced. Test this by removing B, and holding the wax near to A; if the divergence is affected the wax is electrified. The best method of removing the charge is to pass the slab quickly through a Bunsen flame.

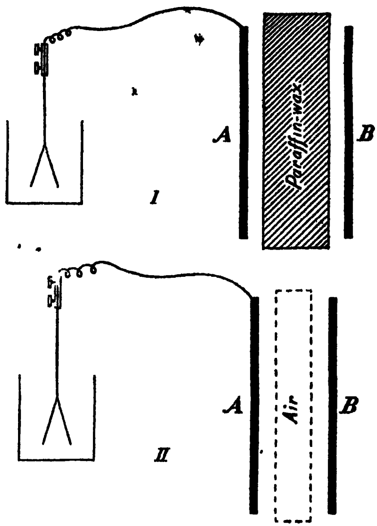


FIG. 55.

Repeat the previous observations at least three times, and enter your results in the following manner

(1) Distance through which B is moved.	(2) Width of Wax slab.	(3) Equivalent Width of Air	$S.I.C. = \frac{(\ )}{(3)}$
1			
2.			
3.			

70. The Field of Force of a Simple Air Condenser

Apparatus required. — Simple condenser. Gilt pith-ball

suspended by silk thread. Electrophorus. Electroscope. Sealing-wax rod.

(i.) **Behaviour of a Pith-ball in the Field of Force.**—Place the plates of the condenser about ·2 cms. apart, and connect plate B to earth. Charge the condenser, and suspend the pith-ball in the field between the plates. Notice how the pith-ball vibrates to and fro.

What is the charge on the pith-ball when in contact with plate A? Why is the pith-ball attracted by plate B? Are the lines of force concerned in this attraction? As soon as the pith-ball touches B, what changes have resulted in the charges of A and B? What is the condition of the charges on A and B after the pith-ball has passed to and fro several times?

(ii.) **Potential Diagram of the Field of Force.**—Fig. 56 represents a potential diagram of the field near to a condenser, plate B being connected to earth. Sketch the potential diagram of the condenser when B has been insulated and moved *nearer* to A. Also sketch the diagram when B has been moved *further away* from A.

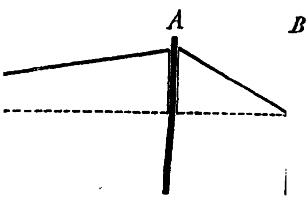


FIG. 56.—Potential diagram of a simple condenser.

(iii.) **Changes in Potential between the Plates.**—Charge the condenser, with the plates about 8 cms. apart. Connect the plate C (Fig. 54) to an electroscope by means of a thin wire; holding it by its insulating handle, place it between A and B, and parallel to both. Observe that the divergence is greater when C is nearer to A, and gradually diminishes as it is moved towards B. While C is in position, remove the connecting wire by means of an insulating handle, and determine whether the charge on the electroscope is + ve or − ve.

Move C to a distance, and connect up to the electroscope again. Without discharging A or B, move B about 16 cms. away from A. Explore the field between A and B as before. The leaves diverge when C is near A, and gradually collapse as C is moved towards B; when moved still nearer to B the

leaves again diverge. Now remove the connecting wire, and determine whether the charge on the electroscope is + ve or − ve.

Additional Exercises

1. A sheet of tinfoil is suspended by a dry silk thread and charged as highly as possible by an electrical machine, but on discharging it only a slight spark is obtained. If the tinfoil is placed on a sheet of dry glass lying on the table, a bright spark can be obtained after the tinfoil has been charged by the machine. Explain the cause of the difference. (1895.)

2. Two similar vertical insulated plates, A and B, are placed parallel to each other and about an inch apart. Each is connected to the cap of a separate gold-leaf electroscope. State and explain the indications of the electroscope when (1) a positive charge is given to A, and afterwards (2) B is touched. (1898.)

3. The inner coating of a Leyden jar is connected by a wire with the prime conductor of an electrical machine and also with a gold-leaf electroscope. If the jar rests upon a sheet of glass, a quarter of a turn of the machine produces a large divergence of the leaves of the electroscope. If the glass be removed, ten turns of the handle are required to produce the same deflection. Explain this. (1888.)

4. Two uncharged insulated brass plates, each metallically connected with the cap of a separate electroscope, are placed parallel to each other. One is charged, and then a plate of shellac is inserted between them. What effects are produced on the electroscopes during these operations? (1895.)

5. Two insulated metal plates are placed facing each other, and each of them is connected with a separate gold-leaf electroscope. If one plate is charged, the leaves of both electroscopes diverge. If now an unelectrified slab of paraffin-wax is introduced between the plates without touching either, state and explain the effect on each electroscope. (1887.)

6. Paraffin has a higher specific inductive capacity than air. If an electrified ball be suspended in an insulated conducting vessel which it does not touch, state what change, if any, is produced in the electrical condition of the system by pouring melted paraffin into the space between the two. (1891.)

7. Two equal horizontal metal discs A and B are placed symmetrically one over the other and separated by air, A being insulated and B earth-connected. When A is charged the plates attract each other. Will the attraction be the same when the space between them is filled with paraffin? Give reasons. (1896.)

CHAPTER XIV

THE INFLUENCE MACHINE, AND EFFECTS PRODUCED BY IT

71. The Theory of the Wimshurst Machine

Apparatus required.—Wimshurst machine. Vulcanite rod. Proof plane. Electroscope.

From theory, it would seem that all metal sectors on either plate, approaching one of the terminals, and after passing the neutralising brushes, are charged similarly. These sectors approaching one terminal are charged + ly, and those approaching the other terminal are charged − ly. Also the sectors which, at any moment, are travelling *from* a terminal to the next neutralising brush are unchanged. These facts may be verified by the following experiments :—

(i.) **Charges acquired by the Sectors.**—Disconnect the Leyden jars from the terminals. When commencing to turn the machine, hold an electrified vulcanite rod near to the front plate and opposite the brush n_3 in order to insure that the terminals become charged as shown in Fig. 57. Cease turning the machine, and quickly touch any sector on the front plate between n_2 and the left-hand terminal with the proof plane. Test the charge on the proof plane by means of a charged electroscope.*

In the same way, observe that any sector on the back plate between n_3 and the left terminal has a similar charge.

Repeat these experiments for any sectors on the front plate between n_1 and the right-hand terminal, and also between n_4 and the left terminal on the back plate.

* If the charge obtained from *one* sector is not sufficient, touch two or three sectors in succession in order to charge the proof plane sufficiently.

Verify that any sectors which have just passed either terminal are either discharged or very nearly so.

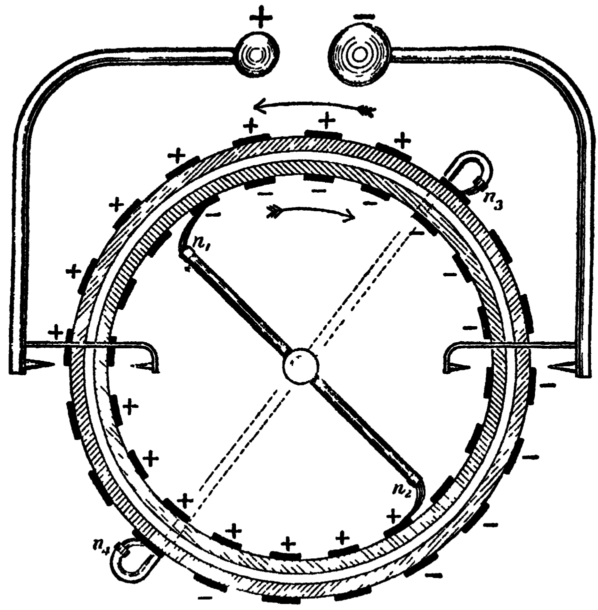


FIG. 57.—Diagram of a Wimshurst machine.

(ii.) **Reversing the Charges at the Terminals.**—The charges on the terminals of the machine may be reversed in the following manner:—Discharge the terminals of the machine. Hold an electrified vulcanite rod near to the front plate and opposite n_4, and turn the machine. With the aid of the proof plane and electroscope now prove that the left terminal is −ly charged, and the right terminal +ly charged.

72. Action of Points

Apparatus required.—Wimshurst machine. Needle. Soft wax. Wax taper. Length of copper wire. Proof plane. Electroscope. Insulated metal disc.

(i.) **Air Currents generated from Points.**—Attach a sewing-needle, or a piece of copper wire with sharpened end to one terminal of a Wimshurst machine by means of soft wax, taking care that the needle is in metallic connection with the terminal. Connect the other terminal to earth. On turning the machine, hold the hand near to the point of the needle, and notice the current of air which appears to be driven from the point. Hold a candle flame near to the point, and observe how it is blown aside.

Transfer the needle to the other terminal, and earth-connect the former terminal.

Observe that the phenomena observed with the − ve terminal are the same as with the + ve terminal.

Attach lumps of soft wax to the point of the needle, and observe how the discharge is prevented.

Bearing in mind the distribution of the charge on a pointed conductor, write a brief account explaining how the above phenomena may be accounted for.

(ii.) **The Air Currents are Charged.**—Allow the current of air from the point to impinge on a small insulated metal plate or sphere. Verify by means of an electroscope that the plate is charged with the same kind of electricity as that of the terminal to which the point is attached. Verify this statement by transferring the needle to the other terminal and testing the charge acquired by the metal plate. Evidently the stream of air which is repelled from the point is electrically charged.

(iii.) **Points Charged by Induction.**—Even if the needle is charged *by induction*, the same phenomena of discharge may be observed.

Hold a needle in the hand, with its point towards the terminal of the machine. Interpose a candle flame between them, and observe how the flame is blown away from the point.

Hold an insulated metal plate between the point and the terminal, and verify that the plate is now charged with the opposite electrification to that which is found on the terminal.

73. Discharge of Electricity through Conductors

Apparatus required.—Wimshurst machine. Two glass rods fixed vertically on stands. Thin string. Five pairs of

pith-balls (on cotton threads) Electrophorus Vulcanite rod

(i.) **Fall of Potential.**—Stretch a piece of thin string AE (1 metre long) between two vertical glass rods (40 cms. high). Connect the ends of the string to the terminals of a Wimshurst machine by means of copper wires. Suspend five pairs of pith balls (on cotton threads) from equi distant points of the

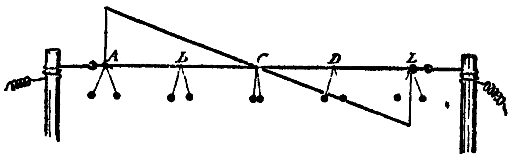


Fig. 58

string. When the machine is in action notice how the greatest divergence is at A and E, less at B and D, and *nil* at C (Fig. 58). Verify that the pith balls at A are charged +ly by bringing near to them the charged plate of an electrophorus, and that the pith balls at E are −ly charged by holding near to them an electrified rod of vulcanite. The sloping line indicates the gradual fall of potential along the string.

Place the finger on the string at C. The divergence of the pith balls is in no case altered, since C is already at zero potential.

(ii.) **Effect of connecting any Point to Earth.** Place the finger at E. State how this affects the pith balls at A, B, C, and D. Draw a diagram showing the fall of potential along the string. How is the potential of E altered when touched by the finger? and in what manner is the potential at other points of the string altered?

(iii.) Place the finger at A. State how this affects the pith balls at B, C, D, and E. Draw a potential diagram of the string. What changes in potential have occurred at various points along the string?

74. Chemical, Heating, and Magnetic Effects of Electrostatic Discharges

Apparatus required.—Wimshurst machine. Copper wire. Insulating stool (a slab of wood, resting on four strong glass

feet, varnished). Bunsen burner. Glass flask (see note 19, p. 223). Glass boiling tube (fitted up as described in note 20, p. 223). Litmus and turmeric paper. Strong solution of sodium sulphate. Sheet of glass. A spiral of one layer of thick cotton-covered copper wire (the spiral should be dipped into melted paraffin-wax, and allowed to cool). Sewing-needle. Large Leyden jar (Leyden battery, if available). Discharging tongs.

(i.) **Heating Effect.**—Connect one terminal of a Wimshurst machine to earth. Stand on the insulating stool, with one hand on the other terminal. Ask another student to turn the machine, and, in a few moments, hold a finger of the free hand near to the top of a Bunsen burner through which the gas is escaping. The spark will ignite the gas.

(ii.) Warm the glass flask (Fig. 59) by holding it in the hands for a few moments, and dip the open end of the glass tube beneath the surface of mercury. Allow the flask to cool sufficiently to draw a short thread of mercury into the tube; this will serve as an indicator for any changes in temperature of the enclosed air. Connect the ends of the wires to the terminals of a Wimshurst machine, and turn the machine for a short time. Notice how the enclosed air expands, showing that the discharge through the strip of foil raises its temperature.

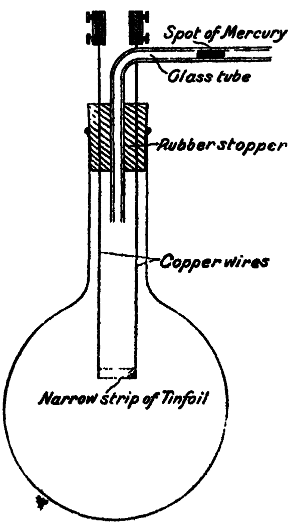


FIG. 59.

(iii.) **Chemical Effect.**—Connect one of the wires, leading from the boiling-tube (Fig. 60), to a terminal of the Wimshurst machine. Connect the other terminal to the inner coating of a Leyden jar standing on the table. Fix an insulated metal knob about 2 or 3 mms. from the knob of the Leyden jar, and connect the insulated knob to the

remaining wire of the boiling-tube. Turn the machine steadily, and notice the small stream of bubbles of gas which are liberated at the ends of the platinum wires. Unless a large machine is available, the volume of the liberated gases will be too small to determine their nature (cp. the Electrolysis of water, by means of a voltaic current).

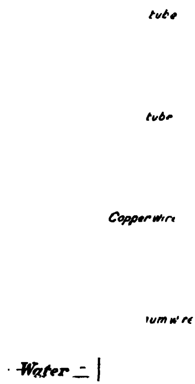


FIG. 60.

(iv.) Dip small pieces of blue litmus paper and of turmeric paper in a strong solution of sodium sulphate. Support the papers, with their edges in contact, on a dry clean sheet of glass. Attach wires to each terminal of the Wimshurst machine; place the free end of the wire from the +ve terminal in contact with the litmus paper, and the end of the wire from the −ve terminal in contact with the turmeric paper. Turn the machine for a short time. Notice that the litmus paper near to the +ve wire is turned red, and that the turmeric paper near to the −ve wire is turned brown. These changes are due to the decomposition of the sodium sulphate, accompanied by the formation of sulphuric acid and caustic soda at the two terminals respectively.*

(v.) **Magnetic Effect.**—Support the wire spiral horizontally on an insulating stand, and connect one end of the spiral to the outer coating of a large Leyden jar standing on the table. Place an ordinary unmagnetised sewing-needle inside the spiral. Connect one terminal of the Wimshurst-machine, by means of a stout copper wire, to the knob of the Leyden jar, taking care that the end of the wire is only in loose contact with the knob, so that it may readily be removed with the discharging tongs.

* *Action of the Current.*—$Na_2SO_4 = Na_2 + SO_4$.
Secondary Actions.—$Na_2 + 2H_2O = 2NaHO + H_2$.
$2SO_4 + 2H_2O = 2H_2SO_4 + O_2$

Connect the other terminal of the machine to earth. Fully charge the Leyden jar, and quickly remove the connecting wire Hold one knob of the tongs in contact with the free end of the spiral, and slowly bring the other knob near to that of the Leyden jar As soon as the spark has passed, remove the needle and prove that it is now permanently magnetised

Additional Exercises

1 An electrical machine is placed in an insulated chamber which is lined inside with tinfoil One terminal of the machine is connected with the tinfoil What will be the effect upon an electroscope placed outside and connected with the chamber when the machine is in action? Explain your answer (1887)

2 Two gold leaf electroscopes, similar in all respects except that a needle projects from the cap of one of them, are placed at equal distances from an electrical machine When the machine is worked both pairs of leaves diverge When it ceases to work one pair of leaves collapses rather quickly and the other pair very slowly Explain this difference in their behaviour (1892)

3 A sharp point is attached to the interior of a hollow metallic sphere Describe and explain the action of the point, (1) when the sphere is electrified, (2) when one end of a brass rod, the other end of which is held in the hand, is cautiously introduced into the sphere through a small hole so as not to touch the sphere and is brought near to the point (1898)

PART III

VOLTAIC ELECTRICITY

CHAPTER XV

CHEMICAL ACTION AND VOLTAIC CELLS

75. Chemical Action

Apparatus required.—Several test-tubes. Dilute sulphuric acid (1 in 8). Commercial zinc. Magnesium ribbon. Copper foil. Bunsen burner.

(i.) **Action of Sulphuric Acid upon Zinc.**— Drop a small strip of commercial zinc into a test-tube containing dilute sulphuric acid (one part of strong acid to eight parts of water). Notice that bubbles of a gas are given off from the surface of the zinc. Close the end of the test-tube with the thumb for a few moments, so as to prevent the gas from escaping. Remove the thumb and hold the open end of the tube at the side of a gas flame. The gas in the test-tube burns with a dull blue flame which is almost invisible. The gas obtained by this means is called *hydrogen*. At the same time observe that the zinc gradually disappears.

This experiment is an example of *Chemical Action;* the zinc is permanently changed; and, on evaporating the clear solution to dryness, a white crystalline solid known as *Sulphate of Zinc* is found.

Hydrogen is one of the constituents of the sulphuric acid, from which it is expelled by the zinc. The burning of

hydrogen is also an example of chemical action; in this case it unites with oxygen in the air, and forms water. Other substances also unite readily with oxygen (or become *oxidised*).

(ii.) **Oxidation of Magnesium.**—Hold a short piece of magnesium ribbon in metal tongs, and ignite one end of the ribbon by holding it in a gas flame. Notice the white powder which is formed when the ribbon burns. In this experiment the magnesium has been *oxidised* to form white oxide of magnesium.

(iii.) **Oxidation of Copper.**—Hold a small piece of copper foil in a Bunsen flame, and notice how the surface is blackened. The black substance formed on the surface is oxide of copper. It is therefore possible to oxidise copper, but the change does not take place so readily as in the case of hydrogen or magnesium.

76. The Simple Voltaic Cell

Apparatus required.—Simple voltaic cell (Fig. 61), fitted with plates of copper and *commercial* zinc. Balance, and box of weights. Two lengths of thin cotton-covered copper wire. Compass-needle.

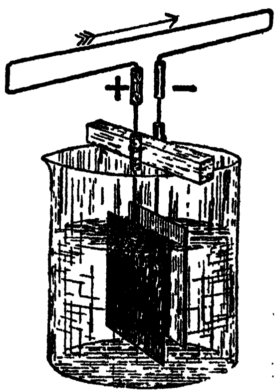


Fig. 61.—Simple voltaic cell.

(i.) **Consumption of Zinc when no Current is passing.**—Carefully dry the zinc plate, and determine its weight. Fix the copper and zinc plates in the wooden support, and immerse them completely in the acid for five minutes *without connecting the plates together.* Remove the zinc plate, rinse it in tap water, then carefully dry and weigh it.

Note the loss in weight of the zinc plate.

(ii.) **Consumption of Zinc when a Current is passing.**—Again fix the copper and zinc plates in the wooden support, and connect a short piece of thin copper

wire to each plate. Immerse the plates completely in the acid, and note the time by your watch. Hold the free ends of the copper wires against the tip of the tongue, and near together; notice the slightly acid taste. Now connect the two wires together (see Fig. 61), and arrange the wire so that it is approximately in the magnetic meridian; hold a small compass-needle immediately under or over the wire, and notice that the needle is deflected towards the east or west. These observations indicate that an *electric current* is traversing the wire.

At the end of five minutes remove the zinc plate, rinse it in tap water, then carefully dry and weigh it. Note the loss in weight of the zinc plate.

From these experiments you will notice that more zinc is used up in Expt. 76, ii. than in Expt. 76, i., showing that the electric current is maintained at the expense of the zinc plate, but that the zinc is even wasted when no current is passing. The experiments in the next section will indicate how this waste may be prevented.

77. Difference between Pure and Commercial Zinc

Apparatus required.—Test-tubes. Dilute sulphuric acid. Pieces of pure and commercial zinc. Iron filings. Mercury.

(i.) **Commercial Zinc and Acid.**—Again notice the action of dilute sulphuric acid upon commercial zinc.

(ii.) **Pure Zinc and Acid.**—Add dilute sulphuric acid to a fragment of pure zinc. Notice that no chemical action takes place. Add a few iron filings, and shake the tube; notice, so soon as the filings touch the zinc, that hydrogen is rapidly given off.

(iii.) **Amalgamation of Zinc.**—Repeat Expt. 77, i., and add a drop of mercury so soon as the chemical action has started. After a short interval the mercury will have spread all over the zinc, and the chemical action then ceases. (This process is termed *amalgamation.*) Add a few iron filings, and notice that the chemical action again takes place.

The rapid action of acid on commercial zinc is probably due to impurities (*e.g.* specks of iron or carbon) in the zinc.

If iron is added artificially to pure zinc (as in Expt. 77, ii.) the result is similar to that observed when commercial zinc is used.

In Expt. 77, iii., the mercury readily forms an *alloy* or *amalgam* with zinc, but will not do so with any iron or carbon which may be present; the latter are therefore protected from the acid by a layer of amalgam. The acid does not act upon the mercury, but under certain conditions it will attack the zinc contained in the amalgam.

78. Improved Simple Voltaic Cell

Apparatus required.—The simple voltaic cell (used in Expt. 76). Mercury.

(i.) Amalgamate the zinc plate of the same cell as that used in Expt. 76. Carefully wash, dry, and weigh the zinc plate. Fit up the cell as in Fig. 61, immersing the plates completely in the acid. Observe the time when the plates are connected together, and allow the current to continue for five minutes. Remove the zinc plate, and again dry and weigh it. Notice that much less zinc has been lost than when the plate was not amalgamated (in Expt. 76, ii.).

79. Polarisation

Apparatus required.—Simple voltaic cell (with amalgamated zinc plate). Tangent galvanometer (see note 26, p. 225). Connecting wires. Solution of potassium bichromate.

In this experiment a *Galvanometer* is used. The principle of this instrument has already been seen in Expt. 76 (ii.), where a compass-needle is deflected out of the meridian by a current traversing a wire placed immediately above the needle; in a subsequent experiment the student will learn how this simple arrangement is elaborated in the modern galvanometer in such a manner as to enable a very weak current to be detected.

(i.) Adjust the galvanometer so that the plane of its coil is in the magnetic meridian. Connect the plates of the cell to the terminals of the galvanometer. Note the deflection of the galvanometer needle at the end of each minute during a period of about fifteen minutes. Notice how the deflection has

diminished. Bubbles of hydrogen gas will be observed on the surface of the copper plate; remove these bubbles by means of a piece of wood or a brush, and notice how the deflection increases.

Pour carefully a small quantity of the solution of bichromate of potash round the copper plate, and again take a series of deflection readings at one minute intervals. Tabulate your observations in the following manner:—

No. of Reading.	Deflection.	
	With Pure Acid.	With Bichromate added.
(1)		
(2)		
(3)		
etc.		

The gradual diminution in deflection, observed when pure acid is used, is due to the accumulation of hydrogen on the copper plate: this constitutes what is termed the *Polarisation* of the cell. The more constant deflection observed when the bichromate of potash is added, is due to the fact that this chemical has the power of *oxidising* the hydrogen (*i.e.* converting it into water), and thereby preventing its accumulation on the copper plate. Other chemicals, besides bichromate of potash, may be used for the purpose of preventing polarisation; and the various types of voltaic cells differ from one another chiefly in the method adopted for preventing it.

80. Voltaic Cells

Apparatus required.—Examples of various cells (*e.g.* Daniell, Bunsen, Bichromate, Leclanché).

(i.) **Daniell Cell** (Fig. 62, i.).—Notice the inner *porous* vessel and the outer vessel of copper. The former contains the zinc and dilute sulphuric acid, while the copper vessel is

protected from the dilute acid by a layer of copper sulphate solution which fills the annular space between the two vessels.

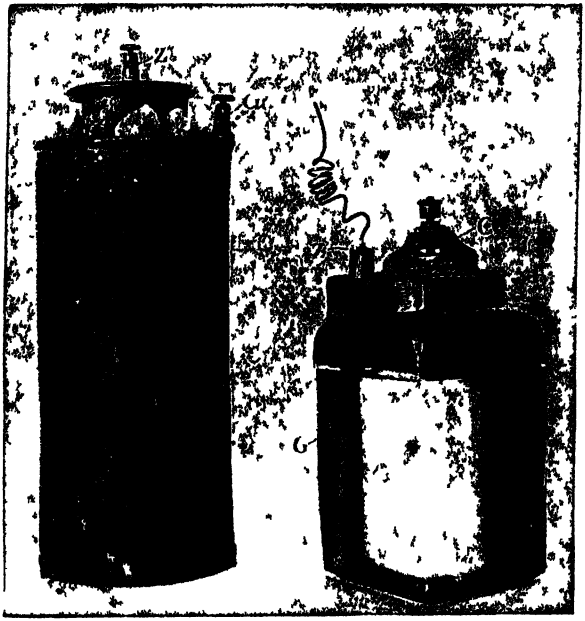


FIG. 62.—(i.) A Daniell cell. (ii.) a Leclanché cell.

The strength of the copper sulphate solution is maintained by placing crystals of the solid sulphate on a perforated shelf near to the top of the cell.

(ii.) **Bunsen Cell** (Fig. 63).—Note the two circular vessels (the inner one porous). The zinc plate is contained, with the sulphuric acid, in the annular space between the vessels. A block of hard carbon (instead of copper) forms the other plate; it is surrounded by strong nitric acid, and both are contained in the inner vessel.

(iii.) **The Bichromate Cell** (Fig. 69).—In the usual pattern of this cell there is one plate of zinc and two plates of carbon

(one on each side of the zinc), all contained in one vessel. The liquid consists of dilute sulphuric acid to which bichromate of potassium has been previously added. When the cell is not in use, the zinc plate must be lifted out of the acid by means of the rod attached to its upper edge—otherwise the zinc will be attacked by the exciting liquid.

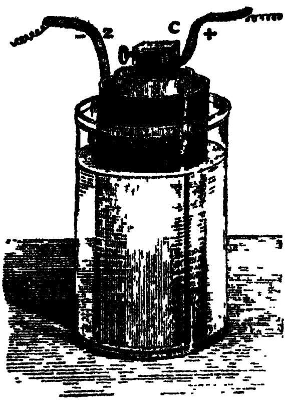


FIG. 63. A Bunsen cell.

(iv.) **Leclanché Cell** (Fig. 62, ii.).—Only one liquid is used in this cell (viz. a solution of ammonium chloride). A zinc rod is immersed in the liquid in the outer glass vessel. A carbon block, surrounded by granular manganese dioxide (which serves to prevent polarisation), is firmly fixed inside the porous earthenware vessel.

(v.) **The Dry Cell** (in some patterns) resembles the Leclanché cell, except that the solution of ammonium chloride is absorbed in plaster of Paris or some other porous material.

Tabulate your observations in the following manner:—

Cell.	Material of the Plates or Rods.	One-fluid or Two-fluid.	Substance used to prevent Polarisation.
(i.) Daniell	Zinc and copper	Two	Copper sulphate.
(ii.)			
(iii.)			
(iv.)			
(v.)			

81. Difference of Potential between the Terminals of a Voltaic Cell

Apparatus required.—Condensing electroscope (see note 22, p. 223). Battery of simple voltaic cells (see note 21, p. 223). Connecting wires. Insulating rod.

Fig. 64 represents a condensing electroscope, of which A and B are the two plates of the condenser, which are separated from each other by a sheet of paraffined paper so as to render the insulation perfect. Plate B is connected by means of a copper wire to a gold-leaf electroscope from

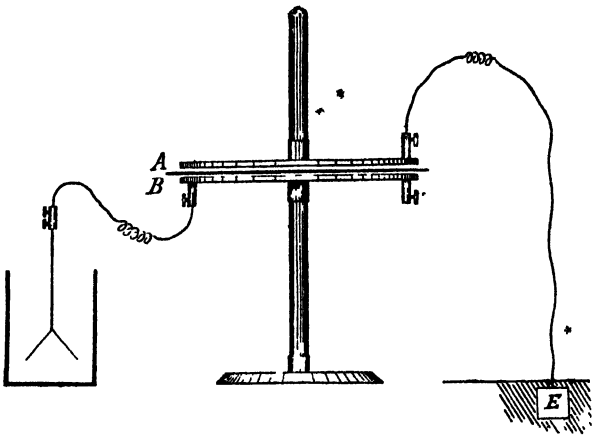


FIG. 64.—A condensing electroscope.

which the disc has been removed. If, when the apparatus is connected up in the manner shown in Fig. 64, a slight charge is given to B no divergence of the leaves will be observed; but if A is now raised, the potential of B will be considerably increased and the leaves will diverge.

(i.) Connect the zinc plate of the first cell to earth, and attach a copper wire to the copper plate of the twenty-fourth cell. Wrap the free end of the latter wire round a rod of vulcanite, which will serve as an insulating handle. Fit up

the condensing electroscope as described on p. 115. Connect the condenser-plate A to earth, and touch the plate B with the

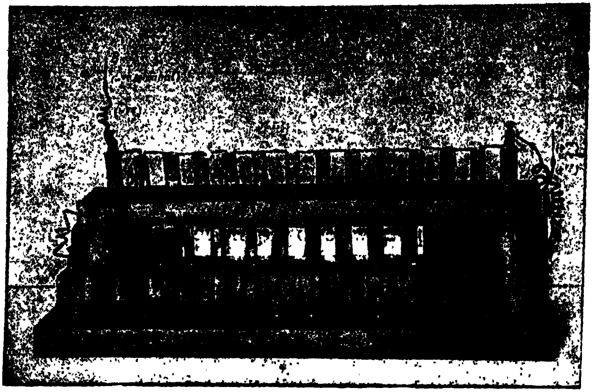


FIG. 95.—A battery of thirty-six simple cells.

free end of the copper wire connected to the twenty-fourth cell (supporting the wire by the vulcanite handle). Raise the plate A, and observe the divergence of the leaves. Disconnect the wire from the twenty-fourth cell, and attach it to the copper plate of the twelfth cell. Discharge the condenser, and touch the plate B with the wire as before. Raise A and observe the divergence; it will be about one-half the divergence observed when twenty-four cells were used. Repeat the experiment, using six (or even fewer) cells. The divergence obtained is evidently proportional to the number of cells used.

Having obtained a divergence of the leaves, determine whether the charge on the leaves is + ve or – ve by holding a charged body near to the instrument. If the charge is found to be + ve it will not only be readily understood why a current traverses a wire connecting the two terminals of a cell, but it will also determine that the *direction* of the current is along the wire *from the copper to the zinc. The copper is termed the positive terminal and the zinc is termed the negative terminal.* In all types of voltaic cells the zinc is always the negative terminal.

The potential difference between the metal plates is sometimes termed the *Electromotive Force* of the cell (and is usually represented by the symbol E.M.F.).

ADDITIONAL EXERCISES

1. How would the action of a Daniell cell be modified if the solution of copper sulphate is replaced by sulphuric acid?

2. Ten simple voltaic cells are connected together *in series*,* and the divergence produced in the leaves of a condensing electroscope is noted when the terminals of the battery have been brought into contact with the plates of the condenser. If the terminals of the battery are connected together for a short time by means of a thick wire, which is afterwards removed, and the previous observation is repeated, the divergence obtained is less than before. Why is this?

3. Connect three Leclanché cells *in series*, and obtain a measure of the potential difference at the terminals by noting the divergence produced in a condensing electroscope. Reverse one of the cells, and repeat the observation. Is the divergence the same as before?

* That is, with the zinc plate of one cell joined to the copper plate of the next, and so on (as shown in Fig. 65).

CHAPTER XVI

MAGNETIC EFFECTS OF AN ELECTRIC CURRENT

82. Direction in which a Magnetic Needle is deflected by an Electric Current

Apparatus required.—A voltaic cell. Commutator (see note 23, p. 224). Cotton-covered copper wire. Compass-needle. Clamp, and piece of cardboard.

A *commutator* (or current reverser, Fig. 66) is required in this experiment. The poles of the battery are connected

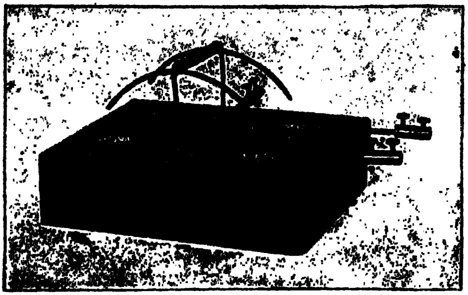


FIG. 66.—A simple form of commutator.

to the ends of the movable arms by means of binding screws, and the terminals of the outer circuit are connected to the free wires dipping into the mercury cups on one side of the commutator. When the arm is in a vertical position the circuit is broken, and no current flows along the wire. If the arm is swung to the left the current will traverse the

outer circuit in the reverse direction to that which is traversed when the arm is swung to the right.

(i.) **Direction of Deflection depends upon direction of Current.**—Connect up the cell and copper wire (AB) to the commutator as shown in Fig. 67. Clamp the cardboard horizontally, so as to serve as a support for the compass-needle. Stretch out a length of the wire AB so that it is horizontal and in the magnetic meridian, and hold it immediately over the compass-needle (C). Now start the current by means of the commutator, and note the direction in which the current is passing, and also the direction in which the *north-seeking* pole of the compass-needle is deflected. Reverse the current by means of the commutator, and repeat the observations. Also, repeat the observations with the wire *below* the compass-needle. Tabulate your observations in the following manner:—

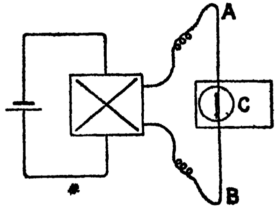


FIG. 67.

Position of Compass-needle	Direction of Current.	Direction of Deflection of N.-seeking Pole of Needle.
Under the wire	N. to S.	
	S. to N.	
Over the wire	N. to S.	
	S. to N.	

Notice how all these results are included in the following rule (*Ampère's*):—*Suppose a man to be swimming in the wire in the same direction as the current, and with his face towards the needle; the north-seeking pole is deflected towards his left hand.*

(ii.) **Deflection depends upon Distance.**—While the current is still passing along the wire vary the distance of the wire from the compass-needle. Notice how the deflection decreases as the distance increases.

(iii.) **Method of increasing the Deflection.**—By referring to the tabulated results obtained in Expt. 82 (i.), it is evident that a current passing *over* the needle, and a current in the opposite direction, but *under* the needle, will both tend to deflect the needle in the same direction. The effect of a weak current may therefore be increased by doubling the wire over and under the needle. Verify this by wrapping the wire several times over and under the needle, and observe how the deflection increases as the number of turns of wire increases.

It would appear from this experiment that the magnetic field due to the current tends to deflect the needle into a direction at right angles to the wire, and that this is more or less prevented by the magnetic field due to the earth. The direction of the magnetic lines of force due to a current may be verified by the following experiment :—

83. Magnetic Field due to a Current

Apparatus required.—Same as in § 82 (a battery is preferable to a single cell).

(i.) Bore a small hole through the cardboard, thread the copper wire through the hole, and clamp the cardboard in a horizontal position. Clamp the wire vertically, and arrange the commutator so that the current is travelling *down* the wire. Place the compass-needle near to the wire, and in successive positions to the north, west, south, and east of it. Note the deflection, if any, in each case. Repeat the observations with the current passing *up* the wire. Tabulate your observations thus :—

Position of Needle.	Direction in which the N.-seeking Pole tends to Point.	
	Current passing *down* Wire.	Current passing *up* Wire.
North		
West		
South		
East		

From this table verify the following rule (known as *Maxwell's Corkscrew Rule*):—*Imagine a corkscrew being screwed along the wire in the direction in which the current is passing. The direction in which the thumb rotates indicates the positive direction of the lines of force.*

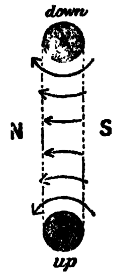


FIG. 68.

84. Magnetic Properties of Solenoids

Apparatus required.—Solenoids (see note 24, p. 224), one of which is suspended as shown in Fig. 69. Voltaic cell. Bar-magnet. Connecting wires.

If a wire conveying a current is bent into a circular form, the space enclosed by the wire will be traversed by lines of force all travelling in the same direction (Fig. 68), and the coil should behave like

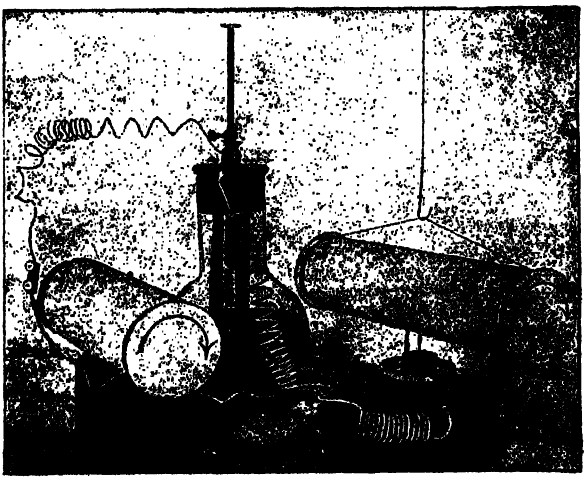


FIG. 69.—Apparatus to illustrate mutual action of two spirals.

a short magnet. The direction of the lines of force suggest

the following rule:—*If the coil is held so that its face is perpendicular to the line of sight, and if the current appears to pass round the coil in a clockwise direction, then that face will have south-seeking polarity. If the direction of the current is anti-clockwise then the face will have north-seeking polarity.* These properties are rendered more evident if the wire is wound into a long solenoid, consisting of several turns of wire.

(i.) **Mutual Action of Solenoids.**—Connect up the apparatus as shown in Fig. 69. Carefully trace out the direction of the current in each solenoid, and verify the magnetic attractions and repulsions, deduced from the above rule, by holding the ends of one spiral near to those of the other.

(ii.) **Action of Magnets upon Solenoids.**—Repeat these observations by holding the poles of a bar-magnet near to the ends of the suspended spiral, and observing the consequent attraction and repulsion.

ADDITIONAL EXERCISES

1. Arrange a given coil of wire with its plane vertical and perpendicular to the magnetic meridian. Pass a constant current through the coil, and map the magnetic field in the neighbourhood of the coil by means of a compass-needle. Reverse the direction of the current and repeat the experiment. (Inter. County Sch., L.C.C. 1900)

2. Repeat the previous experiment, but place the coil with its plane *in* the magnetic meridian.

3. A strong current is sent along a straight wire, stretched horizontally in the meridian, and a dip needle is placed on the west side of the wire and with its plane in the meridian. Will the dip be altered by the current? If so, will the alteration be the same whatever the direction of the current may be?

4. What would be the magnetic effect produced on a straight steel tube by the passage of a strong current through a straight wire placed along the axis of the tube? and how would you prove your statement? (1898.)

5. Suspend a short magnetised needle at the centre of a

circular coil, the plane of which is perpendicular to the magnetic meridian. Determine the time of vibration of the needle. Pass a steady current through the coil, and again determine the time of vibration. From these observations compare the strength of the magnetic field due to the coil, with that due to the earth.

6. Stretch a wire horizontally from east to west (magnetic). Suspend a short heavy magnetised needle immediately over the wire, and determine its time of vibration. Pass a current along the wire from east to west, and again determine the time of vibration. From these observations compare the strength of the field due to the current with that due to the earth. Reverse the direction of the current, repeat the previous observation, and again compare the fields.

Raise the needle vertically through 4 or 5 centimetres, and determine whether the field due to the current is much weaker than before.

CHAPTER XVII

GALVANOSCOPES AND GALVANOMETERS

85. The Sensibility of a Galvanoscope

Apparatus required.—Galvanoscope (see note 25, p. 224). Voltaic cell. Bar-magnet. Lengths of thin German-silver wire. Commutator.

When a galvanoscope is adjusted so that the turns of wire coincide with the magnetic meridian, the amount of de-

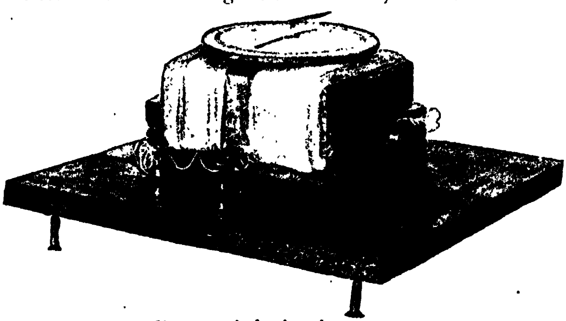


FIG. 70.—A simple galvanoscope.

flection obtained is determined by the relative strengths of the magnetic forces due to the current and to the earth's magnetic field. The former tends to pull the needle into a position at right angles to the meridian, while the latter tends to pull the needle back into the meridian.

These opposing forces may be represented by Fig. 71, in which *ab* represents a narrow coil of wire, and *ns* the magnetised needle. If H and F are the strengths of the magnetic fields due to the earth and to the current respectively,

and if m is the magnetic-pole strength of the needle, then the forces acting on both n and s will be $m \times H$ and $m \times F$. Each pair of forces acts on the needle like a mechanical couple. Each couple tends to rotate the needle in opposite directions, and the needle finally comes to rest in such a position that the moments of these couples round the centre of the needle are equal and opposite.

$$\text{Moment of couple } mH = \text{moment of couple } mF,$$

$$mH \times cd = mF \times ab,$$

or,

$$mH \times 2od = mF \times 2ao.$$

Hence

$$mF = mH \times \frac{od}{oa} = mH \times \frac{an}{oa} = mH \times \text{tangent of angle } aon;$$

or,

$$\text{the tangent of the angle of deflection} = \frac{mF}{mH} = \frac{F}{H}.\text{*}$$

This formula assumes that the magnetic field due to the coil is uniform, but in reality it is only uniform in a very small region round the centre of the coil, and the formula would therefore only hold good if the magnet were very short.

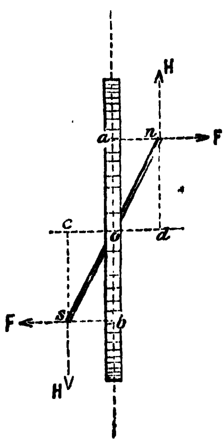


FIG. 71.—The principle of a galvanometer.

The *sensibility* may be defined as *the amount of deflection obtained with a given current of electricity*. The sensibility may therefore be increased either by *increasing* F or by *decreasing* H. F may be increased by making the coil with as many turns of wire as possible; but this can only receive consideration when the instrument is being constructed. H may be diminished conveniently by partly neutralising the earth's field by means of a bar-magnet placed in a suitable position relatively to the suspended needle.

(i.) Connect up the cell (B), commutator (C), galvanoscope

* It will be observed that the deflection is independent of the magnetic strength of the needle.

(G), and a suitable resistance (R)* of thin German-silver wire as shown in Fig. 72. Adjust the galvanoscope so that its coils are in the magnetic meridian, and vary the resistance until a small deflection is obtained (say 15°). See that there are no magnets lying anywhere near the instrument. Tap the instrument gently, and note the scale readings of both ends of the pointer. Reverse the current, and again note the scale readings.

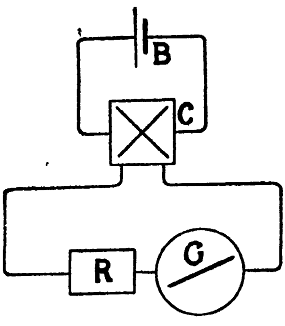


FIG. 72.

Break the circuit. Place a small bar magnet on the table, 25 cms. to the north of the galvanometer needle, with its axis in the meridian and in line with the needle, and with its north-seeking pole towards the instrument. Complete the circuit and again note the deflections as before, both with the current direct and also reversed.

Repeat the previous observations with the magnet at 20 cms. and 15 cms. distant from the needle.

Also, repeat the observations with the magnet clamped horizontally at a height of 20 cms. above the needle, with its axis in the meridian, and with its north-seeking pole towards the north. Tabulate your observations in the following manner:—

Magnet.	Deflections. East End.		Deflections. West End.		Mean Deflection.
Absent	(i.) .	21°	(i.) .	23°	
	(ii.) .	21°	(ii.) .	19°	
	Mean	21°	Mean	21	21°
25 cms.	(i.) .	28°.5	(i.) .	31°	
	(ii.) .	28°	(ii.) .	25°.5	
	Mean	28°.2	Mean	28°.2	28°.2

* A resistance-box is more convenient for this purpose (see p. 139).

86. The Astatic Galvanometer

Apparatus required.—Astatic galvanometer. Voltaic cell. Resistance-box (or a length of thin German-silver wire).

The sensibility of a simple galvanometer may be increased by using an astatic pair of magnetised needles (Fig. 28) instead of a single needle. In such an astatic pair the two needles are approximately alike in dimensions and pole strength.*

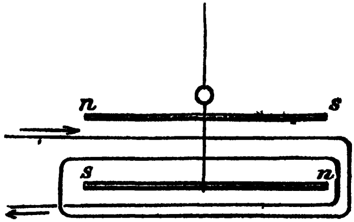


FIG. 73.—The principle of an astatic galvanometer.

If m and m' are the magnetic strengths of the poles of the magnets, the forces due to the earth's field acting on the magnets will be mH and m'H, and the resultant force acting on the astatic pair will be $m\text{H} - m'\text{H}$, or $(m - m')\text{H}$. In an astatic pair $m - m'$ is a small quantity, so that the controlling force due to the earth is very small. Moreover by placing the coil so that its upper layer lies between the needles (Fig. 73), the presence of the upper needle tends to increase the deflection of the lower needle, since, by Ampere's Rule, the deflection of the upper needle, due to a current in the upper layer of the coil will be in the same direction as that of a reversed needle placed below the upper layer of the coil.

The astatic pair is hung by a single silk fibre, the torsion of which is sufficient to mask the controlling effect of the earth's field, and, in fact, it forms the controlling force in the instrument. It must be remembered that, for this reason, the tangent law is not strictly applicable.

(1.) Examine the polarity of the needles of the astatic pair by means of a compass needle. Reverse one of the needles either by untwisting the wire support through two right angles, or by removing one of the needles and replacing it in a reversed position, so that similar poles are pointing in the same direction.

* See p. 49.

Adjust the instrument so that the needles and coil are both in the magnetic meridian, and so that the needles swing quite freely. Note down the zero reading of both ends of the pointer. Connect up the terminals to a small voltaic cell by means of a length of thin German-silver wire, such that the deflection obtained is but small. Note the deflection by reading both ends of the pointer.

Break the circuit, and replace the magnets in their original relative position. Note down the zero readings. Again complete the circuit as before, and notice how much greater the deflection now is. Tabulate your observations in the following manner:

Needles.	Zero Readings.		Deflection Readings.		Mean Deflection.
	East End.	West End.	East End.	West End.	
Similar poles together					
Unlike poles together					

87. The Principle of the Tangent Galvanometer

Apparatus required.—Tangent galvanometer (Fig. 74; see note 26, p. 225). Two or three voltaic cells (of constant E.M.F.). Resistance-box (up to 150 ohms).

In order that a galvanometer may obey the tangent law, it is necessary that the controlling force should be due to a uniform magnetic field (such as that of the earth, and that the field created by the current in the coil should be uniform within the region in which the needle is capable of moving. If the coil is circular and of considerable diameter, the field at its centre due to a current passing round it will be fairly uniform. Hence, if a very short magnetised needle is suspended at the centre of a circular coil, which is placed with

its plane in the magnetic meridian, then all the conditions for an instrument obeying the tangent law will be fulfilled.

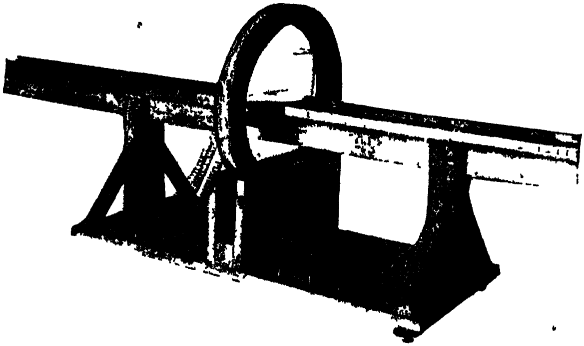


FIG. 74.—A convenient form of tangent galvanometer.

The strength (F) of the magnetic field at the centre of the coil, due to a current passing round the coil, varies directly as the strength (C) of the current, the length (l) of the wire, and inversely as the square of the distance (r) between the wire and the centre of the coil. If the coil consists only of one turn of wire, then $l = 2\pi r$.

$$\text{Hence } F = \frac{C \times 2\pi r}{r^2} = \frac{C \times 2\pi}{r}.$$

If the coil consists of n turns of wire, then

$$F = \frac{C \times 2\pi n}{r}.$$

(i.) **Adjustment of the instrument.**—Adjust the instrument so that the plane of the coil is in the magnetic meridian. Note down the zero readings of both ends of the pointer. Tap the instrument gently with the knuckle, and observe whether the readings have altered.

Cause the needle to swing slightly by holding a pole of a bar-magnet near to the instrument. Remove the magnet to a distance, and again note down the zero readings. Again tap the instrument, and note down the zero readings. If the needle moves quite freely on its pivot, all these readings should be the same.

K

Now, connect up the battery (B), the commutator (C), the resistance-box (R), and the galvanometer (G) by means of cotton-covered copper wires, as shown in Fig. 72. The coil of the galvanometer need not be exactly in the magnetic meridian. Connect up the galvanometer in such a manner that all its coils are in use. Withdraw the plugs marked "50" and "100" from the resistance-box, and pass a current through the galvanometer by completing the circuit by the help of the commutator. Modify the resistance in the circuit until a convenient deflection of from 40° to 60° is obtained.

Break the circuit, and note the scale reading of one end of the pointer (say, $+4°$). Now, note the deflection (say, $+55°$), when the current is in one direction, and (say, $-45°$) when the current is reversed. The actual deflections are $+51°$ and $-49°$. If now the plane of the coil is turned through $\frac{51°-49}{2} = 1°$, the real deflections on either side of the point of rest will be equal. Repeat the observations of the deflections and see whether this is the case.

(ii.) **Effect of increasing the Number of Turns of Wire.**—The effect of increasing the number of turns (n) of wire may be obtained in the following manner: Connect up the apparatus as in the previous experiment, but in this case use only one voltaic cell. Withdraw the plug marked "10," note the deflections when the current is passing in one direction and also when the current is reversed. Repeat these observations, using a different number of turns of wire in (G) in successive observations. Enter the results in the following manner:—

(1) Number of turns (n).	Deflection (a) (2) East End.		Deflection (a) (3) West End.		(4) Mean of (2) and (3).	(5) Numerical value of Tangent of (4).
20	23°.8 23°.3	mean 23°.55	23°.4 24°.0	mean 23°.8	23°.67	0.438

Plot out a curve on squared paper (Fig. 75), with the number of turns as abscissae and the numerical value of tan a as ordinates,

and observe whether the points obtained are in a straight line.

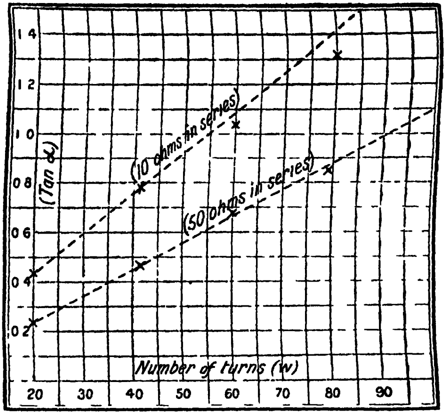


FIG. 75.—Relationship between tan α and the number of turns of wire in a tangent galvanometer.

Draw a straight line through the two lowest deflections, and notice in what manner the curve deviates from this line.

Repeat the previous experiment, but withdraw the plug marked "50" (instead of that marked "10") from the resistance-box. Plot out the readings on squared paper as before, and observe that the points obtained are practically in a straight line.

These experiments indicate that tan α is approximately proportional to the number of turns of wire, if the resistance outside the galvanometer is considerable compared with that of the galvanometer.

(iii.) **Effect of moving the Needle from the Centre of the Coil.**—If the needle is moved along the axis of the coil and away from its centre, the deflection gradually becomes less, and the instrument may be used under such conditions for the comparison of strong currents.

Connect the outer circuit to the first and the last terminals of the galvanometer so that all the coils are in series, and modify the resistance in the box until a deflection of about 60 is obtained when the needle is situated at the centre of

the coil A series of observations may now be taken in order to show how tan α changes when the needle is moved into different positions along the axis of the coil The distances from the centre are read off on the paper scale (attached to the edge of the magnetometer and in front of which a pointer is fixed to the stand of the instrument) Enter the results thus

(1) Horizontal Scale Reading	Deflection (α) (2) East End		Deflection (α) (3) West End		(4) Mean of (2) and (3)	Numerical Value of Tangent of (4)
0	60° 35 59° 75	60° 05	59 9 60 6	60° 25	60° 15	1 739
1	59° 9 59 3	59° 6	59° 5 60 5	60 0	59 8	1 718

Plot out these readings on squared paper, with the horizontal

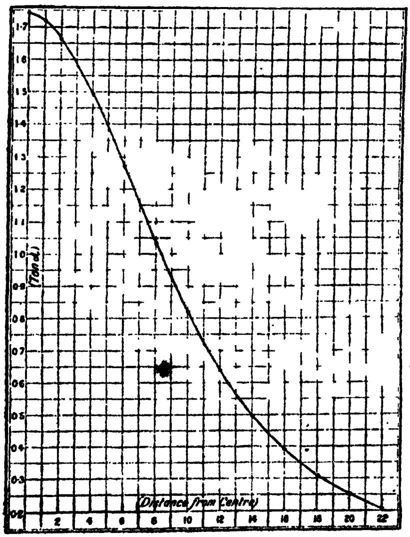


Fig 76 —Relationship between tan α and the distance of needle from centre of coil

scale readings as abscissae, and the values of tan α as ordinates.

Notice the peculiar character of the curve (Fig. 76), which clearly shows that the one quantity is not inversely proportional to the other, but that the relationship is somewhat more complicated.

88. The Mirror Galvanometer

Apparatus required. A galvanometer of the d'Arsonval type is the most convenient. (The construction of a "needle" type of instrument is described in note 27, p. 225.) A voltaic cell. A high resistance (see note 28, p. 227). Lamp and scale (see note 27, p. 226).

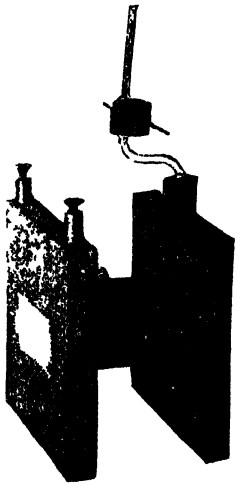


FIG. 77.—A simple type of mirror galvanometer.

(i.) Light the oil lamp, and compare the height of the flame with that of the mirror above the table. Adjust the height of the galvanometer (Fig. 78), so that the mirror is about 2 or 3 cms. higher than the flame. Place the box (A, Fig. 78) in such a position that as little light as possible falls upon the front, and adjust the lamp inside the box so that the flame is edgeways and just behind the slit. Place the galvanometer at least 50 cms. distant from the front of the box, and with the mirror parallel to the plane of the slit. (If the galvanometer is of the *needle* type, the plane of the slit and of the galvanometer coil should coincide with the magnetic meridian; or, if this is not convenient, the position of rest of the mirror may be regulated by means of a controlling magnet placed above, or at the back of the galvanometer. If the instrument is of the d'Arsonval type, these precautions are not required.) Place the eye just over and behind the mirror, and move the slit to one side or the other until a full beam of light falls on the mirror. Place the lens in position in the path of the beam of light, and adjust its position so that a well-defined image of the cross wire is obtained on the plane coinciding

with the slit. Fix the paper centimetre scale (D) in such a position that the image of the wire is focussed on the scale divisions.

Connect up the terminals of the galvanometer with those of

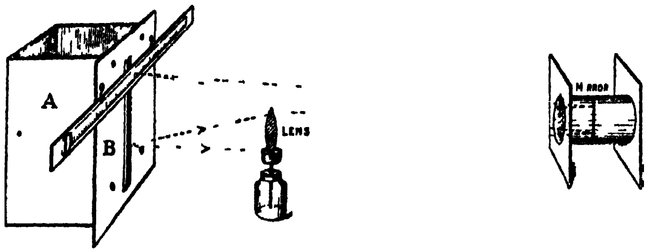


FIG. 78.—Method of observing deflections in a mirror galvanometer.

a single voltaic cell, *including in the circuit a very high resistance* (Fig. 79), and observe whether the image moves freely along the scale both to right and left.

After fitting up the apparatus you will understand that the mirror galvanometer chiefly differs from other types in the method used for observing the deflection of the needle (or coil). The beam of light serves the same purpose as a very long pointer, and, by placing the mirror some distance from the scale, a very small deflection of the mirror causes a considerable movement of the image on the scale. (For further information on the use of a reflected beam of light, see p. 59.)

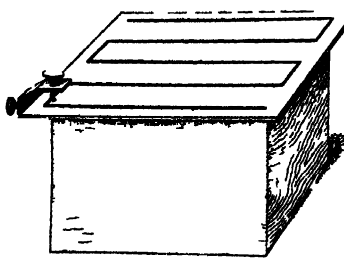


FIG. 79.—A high resistance consisting of pencil lines ruled on *matt* glass.

89. Calibration of a Galvanoscope

Apparatus required.—Voltaic cells (of constant E.M.F.). Resistance-box, or adjustable resistance (see note 29, p. 227). Commutator. Galvanoscope and tangent galvanometer.

It is very seldom found that the deflection produced in a simple galvanoscope is proportional to the current flowing through it. The following experiment indicates how, by passing the same current simultaneously through the galvanoscope and a tangent galvanometer, and by varying the strength of this current, it is possible to obtain a series of readings, which will enable us at any time to compare two currents by observing the deflection of the galvanoscope.

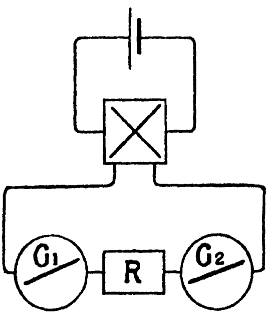


Fig. 80.

(i.) Connect up the high resistance coil of the tangent galvanometer (G_1), the galvanoscope (G_2), the resistance-box, etc., as shown in Fig. 80. Adjust the resistance so that a deflection of about 10° is obtained with the tangent galvanometer. Take simultaneous readings of both instruments. Repeat these observations several times, gradually reducing the resistance until the tangent galvanometer needle is deflected through about 70°. Record your observations in the following manner:—

ce.	Deflection of G_1.		Mean Deflection (a_1).	tan a_1.	Deflection in G_2.		Mean Deflection (a_2).
	East End.	West End.			East End.	West End.	

Plot out a curve (Fig. 81) on squared paper, taking the

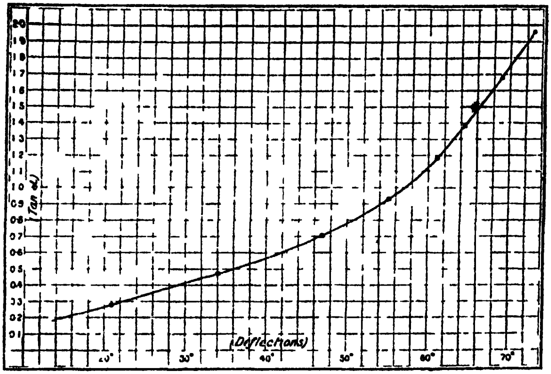


FIG. 81 —Calibration curve of a galvanoscope.

deflections (a_1) as abscissae and the corresponding values of tan a_1, as ordinates.

ADDITIONAL EXERCISES

1. The coil of a tangent galvanometer is placed at right angles to the magnetic meridian, and a steady current passes through it. The needle when set in vibration makes five oscillations in a given time, but only three in the same time when the direction of the current is reversed. Compare the magnetic force at the centre of the coil due to the current with that due to the earth. (1896.)

2. A current flows through tangent galvanometers in series, each of which consists of a single ring of copper, the radius of one ring being three times that of the other. In which of the galvanometers will the deflection of the needle be greater? If the greater deflection be 60° what will the smaller be? (1898.)

3. The coil of a tangent galvanometer is in the magnetic meridian, and a current produces a deflection of 45°. A bar-magnet is placed horizontally, to the south of the coil, with its

axis in the plane of the coil, and with its north-seeking pole towards the coil. The deflection of the needle is now reduced to 30°, although the current has remained unaltered. Compare the strength of the magnetic field at the centre of the coil in the two cases.

CHAPTER XVIII

RESISTANCE. OHM'S LAW

The preliminary experiments in electrostatics have shown that some substances readily conduct electricity, that some are non-conductors, while others can scarcely be classified under either category, but form a separate class of *partial* conductors. This property of a substance may be termed *conductivity*, or the same idea may be expressed in a reverse manner by the term *resistivity* or *resistance* (*e.g.* we may say that silk has *low conductivity* or *high resistance*).

Resistance may be defined as *the property which a body possesses of impeding the discharge of electricity through its substance.*

90. The Resistance of a Wire in Relation to Length, Cross Section and Substance

Apparatus required.—Large Bunsen cell (or an accumulator). Tangent galvanometer (low resistance). Two coils of silk-covered German-silver wire (No. 28 S.W.G.,* and 5 and 10 metres long respectively). One coil of covered German-silver wire (No. 32 S.W.G., and 10 metres long). Coils of covered copper and iron wire (No. 28 S.W.G., and each 10 metres long).

(i.) **Resistance and Length.**—Connect one end of the 5-metre length of German-silver wire (No. 28) to one pole of the cell, and connect the other end to a terminal of the short thick coil of the galvanometer. Connect the other terminal of the

* The letters S.W.G. indicate the *Standard Wire Gauge.*

cell and the galvanometer together by means of a short copper wire. The tangent of the angle of deflection is a measure of the magnitude of the current. Note the deflection.

Insert the 10-metre length of German-silver wire (No. 28) in the circuit instead of the 5-metre length. Note the deflection.

These observations show that the resistance increases when the length is increased.

(ii.) **Resistance and Diameter.**—Repeat the previous observations when the current traverses 10 metres of No. 32 German-silver wire. Note the deflection, and compare this with the deflection obtained when the same length of No. 28 wire was used. Observe that the diameter of No. 32 wire is less than that of No. 28.

The experiment indicates that the resistance increases when the diameter is diminished.

(iii.) **Resistance depends upon the Metal.**—Repeat the observations with 10 metres of No 28 iron wire, and with the same length of No. 28 copper wire. Note the deflection in each case, and compare these with the deflection obtained with the same length of German-silver wire of the same diameter.

The experiment indicates that the resistance of iron is less than that of German-silver, and that the resistance of copper is less than that of iron.

Tabulate your observations in the following manner:—

Length.	Material.	Size.	Deflection (a).	tan a.
5 metres	German silver	No. 28		
10 ,,	,,	,,		

The student will now be able to understand the principle of the *Resistance-boxes*, which are so frequently used in experimental work. Several thick brass connecting pieces

are mounted on the ebonite lid of the box, and the space between each pair of pieces is occupied by a well-fitting brass plug. If the lid is removed it will be seen that consecutive ends of the brass pieces are joined together by a length of thin German-silver (or, sometimes manganin *) wire wound round a bobbin. If any plug is removed from the lid, the current must pass through the coil which bridges the gap, and which offers resistance to the passage of the current. If the plug is inserted into the gap, the current passes through the plug (which offers very small resistance compared with the coil †). The various coils contain different lengths of wire of different thicknesses, and are carefully adjusted so that their resistances have the relative numerical values which are indicated on the lid of the box. The *Unit of Resistance* (which is called the *Ohm*) will be explained in a subsequent chapter; but the student may form an idea of the resistance represented by the ohm by remembering that 92.3 centimetres of No. 28 German-silver wire have a resistance of approximately one ohm. The numbers stamped on the lid of a resistance-box indicate the resistance (in ohms) of the coil underneath.

91. Resistance of a Simple Voltaic Cell

Apparatus required.—Tangent galvanometer. Simple voltaic cell (as described below). Very dilute sulphuric acid (in which a little potassium bichromate is dissolved). Pipette.

Simple Voltaic Cell.—Fill a wide shallow beaker to a depth of 2 inches with clean white sand. The sand serves as a convenient means of supporting the zinc and copper plates of the simple voltaic cell, since the depth of immersion and the distance apart of the plates can thus be readily adjusted.

* Manganin is an alloy consisting of 84 parts of copper, 12 of nickel, and 3.5 of manganese.

† The student will notice that there are two paths open to the current—it may traverse both the coil and the plug. If the resistance of the paths were equal the current would divide itself equally between them. In the present case the resistance of the plug is negligibly small compared with that of the coil, therefore practically the whole of the current will traverse the plug. The plug constitutes what may be termed a "low-resistance *shunt* circuit."

Connect the supporting wires soldered to the plates to wires leading to the galvanometer by means of binding screws. If a copper plate is not available, a piece of stout copper wire will serve satisfactorily the requirements of the experiment.

(i.) Pour sufficient acid into the beaker so as just to cover the zinc and copper plates, and connect the plates to the terminals of the low-resistance coil of the galvanometer. Place the plates close together and observe the deflection. Separate them gradually and observe how the deflection diminishes, showing that the resistance of the cell is increased when the length of the liquid column between the two plates is increased.

Now raise the plates slightly so that a smaller area is immersed. Notice how the deflection diminishes as the cross-section of the liquid column between the plates becomes less.

This explains the advantage of using a large cell instead of a small one. The E.M.F. of the cell simply depends upon the materials used, and is quite independent of the *size;* but the resistance depends very largely upon the size, and only becomes negligible when a cell with large plates close together (such as those of an accumulator) is used.

92. Ohm's Law

Apparatus required.—A length of No. 32 German-silver wire (2 metres long), stretched between terminals fixed into a board, and with a centimetre scale fixed under the wire (a potentiometer may be used for this experiment). An adjustable resistance (a carbon-block resistance is suitable). Tangent galvanometer (with three or four turns of wire). Three voltaic cells of constant E.M.F. Three standard cells (Clark, or Calomel type; see note 32, p. 227). Mirror galvanometer. High resistance (see note 28, p. 227).

G. S. Ohm, in 1826, conducted original experiments on the conductivity of different metals, on the effect of varying the cross-section of the wires, and on the relation between the current created in a wire and the potential difference between the ends of the wire. The latter experiments resulted in the statement of a simple relationship which is usually termed *Ohm's Law.* This law may be expressed

thus: *In any wire, at uniform temperature, the current is directly proportional to the potential difference between its ends;* or, $\frac{E}{C}$ is a constant ratio

(where E and C represent the potential difference and the current respectively).

The numerical magnitude of the ratio $\frac{E}{C}$ is a measure of the *Resistance* of the conductor.

The constancy of the ratio $\frac{E}{C}$ may be proved by applying the following principle: If any two points (A and C, Fig. 82) on a wire, AB, conveying a current, are touched by the

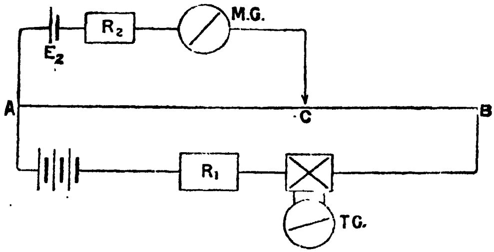


FIG. 82. Proof of Ohm's law.

ends of a long thin wire, AR_2C, a weak current will be generated and will traverse the thin wire from A to C. This weak current may be detected by including in its path a delicate galvanometer (MG). We can also include in the same circuit another source of electromotive force, E_2 (say, a standard cell), placed so as to tend to send a current in the opposite direction. If this *opposing* electromotive force is equal to that due to the potential difference between A and C, then no current will traverse the wire, and no deflection will be produced in the galvanometer. By varying the point of contact C, a point may be found such that no deflection is obtained, and the potential difference between A and C is equal to the electromotive force of one standard cell. The strength of the current along AB may be

observed by including a tangent galvanometer (TG) in the circuit.

If *two* standard cells in series are used instead of E_2, and if the point of contact (C) remains fixed, it will be found necessary to *double* the strength of current passing along AB in order to obtain no deflection in MG. If *three* standard cells are used, the current in AB must be made three times as great.

(i.) Connect up the apparatus as shown in Fig. 82, and adjust the resistance R_1 so that a deflection of about 15° is obtained in TG. Find a point C such that no current traverses MG when one standard cell is used. Carefully read the deflection in TG, and also when the commutator is reversed.

Insert *two* standard cells in place of E_2. Make contact at the same point C, and reduce the resistance R_1 until there is no deflection in MG. Again read the deflections in TG as before.

Repeat, with three standard cells. Enter your observations in the following manner: -

Standard Cells (n).	Deflection in TG.		Mean Deflection.	tan a.	$\frac{n}{\tan a}$.
	East End.	West End.			
1	{10, 12°.1} 11.05	{12.4, 10} 11.2	11.1	0.196	5.102
2	{20°.5, 22.2} 21°.3	{22°.8, 20} 21.4	21°.35	0.391	5.115
3	{30°, 30°.8} 30°.4	{32°.4, 28°.5} 30°.4	30.4	0.587	5.110

93. Further Experiments on Ohm's Law

Apparatus required.—Voltaic cells (at least three, and of low internal resistance). Resistance-box. Commutator. Tangent galvanometer (with low resistance coil).

If the units of current, electromotive force, and resistance are suitably chosen, then Ohm's Law may be expressed thus: $C = \frac{E}{R}$ or $E = C \times R$ (where C = strength of current, E = electromotive force of battery, and R = total resistance in the circuit).

(i.) **If E remains constant, then the product $C \times R$ is constant.**—Connect up one voltaic cell to the commutator, and connect this to the low resistance coil of the galvanometer and to the resistance-box (as shown in Fig. 72). Withdraw the 50-ohm plug, and observe the deflection of both ends of the pointer, with commutator up and with commutator down. Repeat the observations with 100 ohms in circuit, and also with 150 ohms in circuit. Record your observations thus:—

Resistance (R).	Deflections		Mean Deflection (a).	tan a.	R × tan a.
	East End.	West End.			

(ii.) **If R remains constant, the ratio $\frac{E}{C}$ is also constant.**—Connect up three voltaic cells in series, and complete the circuit through the commutator, resistance-box, and the *high* resistance coil of the tangent galvanometer, as in Expt. 93 (i.). Withdraw the plugs from the resistance-box until a resistance of about 150 ohms is in circuit, and increase this (if necessary) until a deflection of about 60° is obtained. Note the deflections as before, and repeat the observations with two cells, and with one cell in circuit. Record your observations thus:—

Number of Cells (N).	Deflections.		Mean Deflection (a).	tan a.	$\frac{N}{\tan a}$.
	East End.	West End.			

Notice that, in this experiment, cells of *low* internal resistance are used. This is necessary since the *total* resistance must remain approximately constant, and this can only be so if the internal resistance of the cells is negligible compared with the total resistance in the circuit.

94. Fall of Potential along a Uniform Straight Wire conveying a Current

Apparatus required.—Two or three voltaic cells (of constant E.M.F.). Thin German-silver wire (1 metre long) stretched between two binding screws and over a metre scale. Tangent galvanometer of high resistance (or the galvanoscope may be used, if previously calibrated, and if of high resistance). Commutator. Connecting wires.*

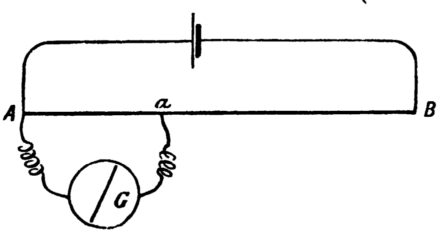


FIG. 83.

If AB (Fig. 83) represents a long wire of uniform

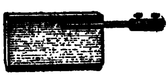


FIG. 84.

* More trustworthy observations are obtained if the galvanometer wires terminate in contact-pieces (Fig. 84). These may readily be made from stout sheet brass, with the lower edge filed to a V-shaped edge, and with a piece of thick copper wire soldered to one side of the sheet.

material and cross-section, the resistance of each unit of length is the same. If a current traverses the wire, the strength of the current is the same in each unit of length, and the potential difference between the ends of each unit length must be the same: in other words, the fall of potential along the wire must be uniform. This may be represented in a diagram (Fig. 85) in which the length of the horizontal line represents the resistance of the wire, and those of the vertical lines represent the potentials at various points along the wire. The potential difference between any two points (A and B) will be represented by V_1a, and the diagram shows that V_1a depends upon the distance between A and B. If the fall of potential along the wire is uniform, the ratio $\frac{V_1a}{AB}$ should therefore have a constant value.

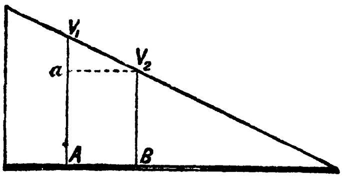


FIG. 85

The potential difference between various points may be compared by touching pairs of points with the ends of wires connected to the terminals of a tangent galvanometer, in which the current generated will be proportional to the potential difference between the ends of the wires.

(i.) Connect up the apparatus as shown in Fig. 83. Take a series of readings, noting in each case the distance A*a* and the deflection produced. Enter your observations in the following manner:—

Distance A*a*.	Deflections.		Mean Deflection (*a*).	tan *a*.	$\frac{\tan a}{Aa}$
	East End.	West End.			

95. Fall of Potential along two Wires connected in Parallel

Apparatus required.—Voltaic cells. Commutator. Two lengths (say, 100 cms. and 50 cms. long respectively) of thin German-silver wire, each stretched on a board between binding screws and over centimetre scales.

If a number of conductors are arranged with their ends in contact, so that a current entering at one end has several paths open to it, they are said to be arranged *in parallel* or *in multiple arc*. Fig. 86 represents a voltaic cell AB,

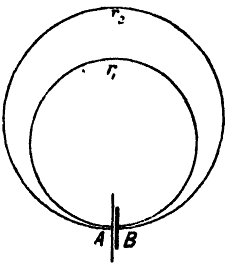


FIG. 86.

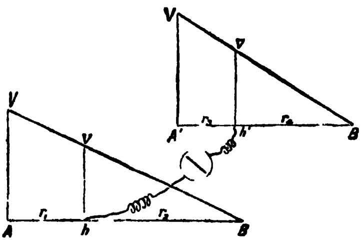


FIG. 87.

with its poles connected together by two wires in multiple arc, and the resistances of these wires may be represented by the symbols r_1 and r_2. Let the resistances of these two wires be represented by the lengths of the lines AB and A′B′ (Fig. 87). The potentials at A and A′ are equal, so also those at B and B′. Imagine that a terminal wire of a galvanometer is connected to a point h on the wire AB, and that the other galvanometer wire is connected to a point h' on the wire A′B′. A current will pass through the galvanometer unless h and h' are at the same potential, *i.e.* unless $hv = h'v$. Imagine that the point h' has been found such that no deflection is observed on the galvanometer. Then

$$\frac{hv}{\mathrm{AV}} = \frac{h'v}{\mathrm{A'V}}.$$

But, from geometry, $\dfrac{hv}{\mathrm{AV}} = \dfrac{\mathrm{B}h}{\mathrm{BA}}$, and $\dfrac{h'v}{\mathrm{A'V}} = \dfrac{\mathrm{B'}h'}{\mathrm{B'A'}}$.

Therefore $\frac{Bh}{BA} = \frac{B'h'}{B'A'}$. This may also be written

$$\frac{BA}{Bh} = \frac{B'A'}{B'h'}.$$

Subtract unity from both sides, $\frac{BA}{Bh} - 1 = \frac{B'A'}{B'h'} - 1$;

or, $$\frac{BA - Bh}{Bh} = \frac{B'A' - B'h'}{B'h'};$$

or, $$\frac{Ah}{hB} = \frac{A'h'}{h'B'};$$

or, $$\frac{r_1}{r_2} = \frac{r_3}{r_4}.$$

(i.) Connect up the apparatus as shown in Fig. 88. Having selected any point h, on one wire, make contact at some point, h', near to one end of the other wire, and note the direction of the deflection; make contact at a point near

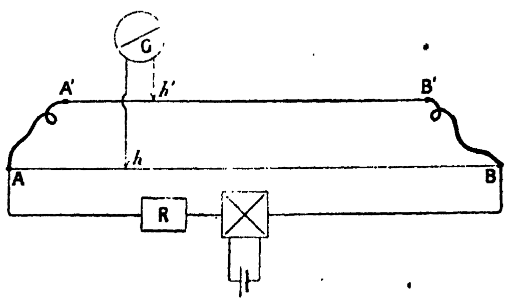


FIG. 88.

to the other end of the wire A'B', when the deflection is probably reversed, showing that the desired point is somewhere between these two points of contact. Now touch at other pairs of points on A'B' nearer together, until a point is reached at which there is no deflection. Read off the distances Ah and A'h'. Tabulate your observations in the following manner :—

Length Ah.	Length $A'h'$.	Ratio $\frac{Ah}{hB}$.	Ratio $\frac{A'h'}{h'B'}$.

96. Wheatstone's Bridge

Wheatstone's Bridge is a practical application of the theoretical result obtained in the previous section. Fig. 89 represents a simple form of the bridge. It consists of a length of German-silver wire stretched along a board, and the ends of the wire are soldered to metal strips to which

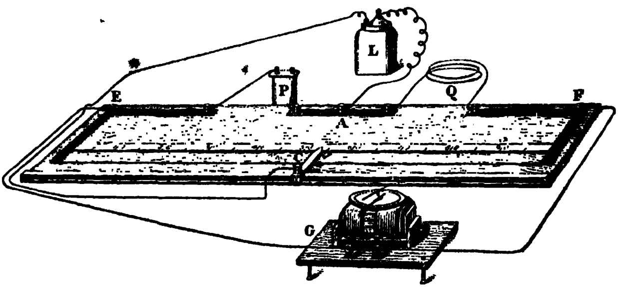


FIG. 89.—A Wheatstone Bridge, together with the necessary connections.

binding screws are attached. The wire may be 50 cms. or 100 cms. long, and a wooden scale is placed under the wire to enable exact lengths of the wire to be used in experiments. The two resistances P and Q to be compared are connected to binding screws as indicated in the diagram. The galvanometer is connected to the binding-screws at E and F. One pole of the voltaic cell is connected to A, and the other pole is connected to a long wire, the free end of which is brought into contact with various points of the

German-silver wire EF. The divided circuit consists of the two paths APEC and AQFC. When the point C has been found such that no deflection is observed, then

$$\frac{P}{Q} = \frac{EC}{CF}.$$

The lengths of EC and CF are given by the wooden scale, and the ratio of their resistances is the same as the ratio of their lengths. Hence the ratio $\frac{P}{Q}$ is determined.

UNITS OF CURRENT, QUANTITY, ELECTROMOTIVE FORCE, AND RESISTANCE

Electromagnetic Units

(i.) **Current.**—A current has unit strength when 1 cm. length of its circuit, bent into the form of an arc of 1 cm. radius, exerts a force of 1 dyne * on a unit magnet-pole † placed at the centre of the arc.

(ii.) **Quantity.** Unit quantity is that which is conveyed by the unit of current in one second.

(iii.) **Electromotive Force.**—The unit difference of potential exists between two points when unit work (one erg ‡) has to be done in order to convey one unit of quantity between the two points.

(iv.) **Resistance.**—A conductor has unit resistance when unit difference of potential between its ends causes a current of unit strength to flow through it.

Practical Units

The Practical Unit of Current.—The electro-magnetic unit of current defined above is found to be too large for practical purposes, and another unit is universally adopted

* The *dyne* is the absolute unit of force; it is approximately equal to the weight of 1 milligram.

† A magnet pole has unit strength when it repels an equal similar pole, placed 1 cm. distant, with a force of one dyne.

‡ The *erg* is equal to the work done by one dyne in moving through a distance of 1 cm.

which is equal to $\frac{1}{10}$ part of the electro magnetic unit. This practical unit is called the *Ampere*.

The Practical Unit of Quantity.—The *electro magnetic* unit of quantity has been defined as the quantity conveyed by unit current in one second. The *practical* unit of quantity is that which will be conveyed by one ampere in one second, and is therefore equal to $\frac{1}{10}$ part of the electro magnetic unit of quantity. This unit is called the *Coulomb*.

The Practical Unit of E.M.F. (or Potential Difference).—The electro-magnetic unit (p. 150) is far too small for practical purposes, and a much larger unit is adopted which is equal to 10^8 electro magnetic units. This larger unit is called the *Volt*. (In order to express very large numbers it is convenient to use the index system of notation—thus 10^8 is the index notation representing 10 multiplied by itself 8 times, *i.e.* 100,000,000. The volt is therefore equal to one hundred million electro magnetic units.)

The student may form a mental conception of the magnitude of the volt by the fact that the E.M.F. of the Daniell cell is 1·07 volts, the Grove cell 1·95 volts, the Bunsen cell 1·94 volts, and the Leclanché 1·46 volts.

The Practical Unit of Resistance.—A conductor is said to possess the practical unit of resistance when a potential difference of one volt between its ends will cause a current of one ampere to flow through it. This unit is called the *Ohm*.

ADDITIONAL EXERCISES

1. A wire AB of 0·33 ohm resistance, forms part of a circuit through which an electric current flows in the direction from A to B. The points A and B are also connected by another conducting path, in which is included a cell of E.M.F. 1·287 volts and a galvanometer, the positive pole of the cell being that joined to A. If the galvanometer is not deflected, what is the strength of the current in the wire AB? (1897.)

2. A square sheet of tinfoil is fixed to the surface of a glass plate, and the middle points of opposite edges of the foil are connected to the terminals of a battery. With the aid of a

sensitive galvanometer and a pair of needles, trace out the lines of equal potential in the foil.

3. A coil of six turns, each of which is 1 metre in diameter, deflects a compass needle at its centre through 45°. Find the strength of the current in ampères, having given that H = 0.18 C.G.S. units. (1892.)

CHAPTER XIX

EXPERIMENTS WITH THE WHEATSTONE BRIDGE

97. The Construction of a 1-Ohm Coil

Apparatus required.—Wheatstone bridge. Galvanometer. A standard 1-ohm coil. German-silver or manganin wire (No. 28 is a convenient size). Wooden cylinder (Fig. 90). Thick copper wire.

(i.) Connect up the apparatus as shown in Fig. 89. Measure out 1 metre of German silver-wire (No. 28), and remove the silk covering from the ends. Insert the wire in the gap Q, and find the point of contact on the bridge wire, which gives no deflection in the galvanometer. Calculate the resistance of the wire by means of the formula $\frac{P}{Q}=\frac{EC}{CF}$ (see p. 150), and note that the resistance is rather greater than one ohm. Shorten the wire slightly, and again determine its resistance. Repeat this until no deflection is obtained when the point of contact is exactly at the middle of the bridge wire.

Before removing the wire from the bridge, bend the ends of the wire to a right angle just where the wire leaves the binding screws. Solder to the end of each wire a length (10 cms.) of thick copper wire, adjusting the wire so that the soldering terminates at the points where the wire is bent. Carefully wash the soldered joints in water. Insert the copper wires through the holes bored in the ends of the wooden cylinder provided. Double

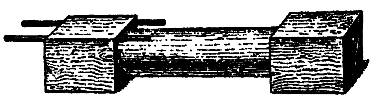


FIG. 90.

the wire together at its middle point, then wrap it round the cylinder, and tie it in position with cotton thread. Re-determine the resistance as accurately as possible, and write this in pencil on the cylinder.

98. The Resistance of a Wire varies directly as the Length, and inversely as the Cross-section

Apparatus required.—Wheatstone bridge, etc. Standard resistance. German-silver wire (Nos. 28 and 32). Metre scale. Micrometer wire guage. Solution of caustic potash.

(i.) **The Resistance varies directly as the Length.**—Cut two pieces (of different length) of No. 28 German-silver wire. Bare the ends of the wires, and bend the bared ends to a right angle. Measure the length (between the bends) of each wire. Measure the resistance of each wire, taking care that the wire leaves the binding screws of the bridge just where the bend is situated. Enter your results thus :—

	Length (L).	Resistance (R.)	$\frac{R}{L}$
1			
2			

(ii.) **The Resistance varies inversely as the Cross-section.**—Cut two *equal* lengths of Nos. 28 and 32 German-silver wire. Remove the insulation from the ends of the wires by dipping them into a hot solution of caustic potash. (The use of a knife might alter the diameter.) Measure the diameter (d_1 and d_2) of each wire at three different points, and take the mean value as the true diameter in each case. Calculate the cross-section of each wire by means of the formula, *Cross-section* $= \left(\pi \times \frac{d^2}{2}\right)$.

Measure exactly equal lengths of the wires, and determine their resistances. Enter your results thus :—

Diameter (d).	Cross-section (s).	Resistance (R).	($s \times$ R).
1			
2			

N.B.—Retain the two wires for the requirements of the next experiment.

99. The Resistance of two Wires in Parallel

Apparatus required.—The same as in previous experiment.

If a number of conductors are arranged with their ends in contact, so that a current entering at one end has several paths open to it, they are said to be *in parallel* or *in multiple arc.* Fig. 86 represents a voltaic cell AB, with its poles connected together by two wires in parallel, the resistance of which are r_1 and r_2. The potential difference between the ends of the wires is the same in both cases; let it be denoted by E.

If c_1 is the current traversing the wire r_1, then $c_1 = \dfrac{E}{r_1}$.

If c_2 ,, ,, ,, r_2, ,, $c_2 = \dfrac{E}{r_2}$.

The total current C traversing the circuit is equal to the sum of c_1 and c_2;

$$\text{or, } C = c_1 + c_2 = \frac{E}{r_1} + \frac{E}{r_2} = E\left(\frac{1}{r_1} + \frac{1}{r_2}\right) = E\left(\frac{r_2 + r_1}{r_1 r_2}\right) = \frac{E}{\dfrac{r_1 r_2}{r_1 + r_2}}.$$

Hence *the combined resistance of two wires in parallel is equal to their product divided by their sum.*

(i.) Insert the two wires (of which the resistances, r_1 and r_2, are known) in parallel between the binding screws of the bridge. Measure the resistance. Enter your results thus:—

r_1.	r_2.	Resistance in Parallel.	
		$\frac{r_1 r_2}{r_1 + r_2}$ (calculated).	By Experiment.

100. Specific Resistance of a Metal

Apparatus required.—The same as in Expt. 98.

The *Specific Resistance* of any metal is the resistance of a cube of the metal, each edge of the cube being 1 cm. long. Such a cube may be regarded as a wire 1 cm. long and 1 sq. cm. cross-section; if the dimensions of the wire are altered to l cms. in length and s sq. cms. in cross-section, then

$$\text{Resistance (R)} = \text{Specific resistance } (k) \times \frac{l}{s},$$

or,

$$R = \frac{kl}{\pi r^2}.$$

In order to determine k for any metal, it is necessary to measure the length, cross-section, and resistance of a piece of that metal in the form of a wire.

(i.) Measure the length, cross-section, and resistance of a piece of German-silver wire by the method described in Expt. 98. Enter your results thus:—

Metal.	Length (l).	Cross-section (πr^2).	Resistance (R).	$\frac{R \times \pi r^2}{l}$.

N.B.—It is usual to express the specific resistance of a metal in *millionths* of an ohm (or, *microhms*). Therefore the recognised result will be obtained by multiplying the value of $\left(R \times \frac{\pi r^2}{l}\right)$ by 10^6.

101. The Effect of Change of Temperature on the Resistance of a Wire.

Apparatus required.—Spiral of iron wire fitted as shown in Fig. 91 (see note 30, p. 227). Wheatstone bridge, and accessories. One-ohm coil.

(i.) Place a deep beaker full of water on a tripod, and fix the tube containing the wire spiral in the water. Connect up the ends of the spiral by means of thick copper wires to the binding screws of the bridge. After the tube has been in the water for about five minutes, stir the paraffin oil, and note the temperature. Measure the resistance of the spiral. Slowly warm the water, and frequently stir the oil. When the temperature has risen about 10° C., remove the flame, stir the oil and repeat the observations of temperature and resistance. Repeat these readings at higher temperatures. From the first and the last observations

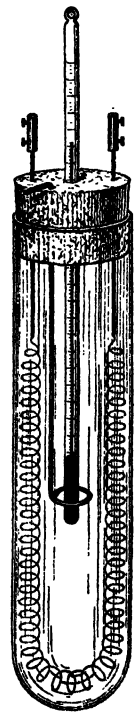


FIG. 91.—Apparatus to show alteration in resistance due to change of temperature.

determine how much a wire of 100-ohms resistance would increase in resistance due to a change in temperature of 1° C, thus, $\frac{R_2 - R_1}{R_1} \times \frac{100}{(T_2 - T_1)}$.

Enter your observations thus

Temperature	Resistance	Per cent increase due to rise of 1° C

Fig. 92.—Apparatus to determine resistance of liquids

102. Specific Resistance of Liquids *

Apparatus required Two voltaic cells (of constant E M F) or accumulators. Resistance-box. Galvanoscope (or tangent galvanometer) Long glass tube, arranged to contain the electrolyte (see note 31, p 227) Solution of copper sulphate (20 per cent) Burette Metre scale

The resistance of a column of liquid (R) =

$$\frac{\text{Specific resistance } (k) \times \text{length of column } (l)}{\text{Cross-section } (\pi r^2)},$$

or,

$$k = \frac{R \times \pi r^2}{l}$$

(1) Determine the cross-section of the tube (Fig. 92) in the following manner — Clean the tube, insert a cork in the lower end, and clamp it in a vertical position. By means of a burette, pour exactly 100 c.c. of water into the tube, and measure the

* This experiment is inserted here in order to contrast the method of determining the specific resistance of solids with that of electrolytes

height (h) to which the water rises. Then, height (h) × cross-section (πr^2) = 100 c.c., or

$$\pi r^2 = \frac{100}{h} \text{ sq. cms.}$$

Dry the tube, insert the lower terminal, and nearly fill the tube with the solution of copper sulphate. Connect up the cells, galvanometer, resistance-box, and glass tube in series. Adjust the copper discs about 40 cms. apart, and vary the resistance in circuit until a deflection of about 40° or 50° is obtained. Note the deflection. Mark the position of the upper disc by attaching a piece of gummed paper outside the tube. Increase the resistance in the box by about 50 ohms, and notice how the deflection is diminished. Lower the upper disc until the deflection is the same as before. Measure, by means of a scale, the distance through which the disc has been lowered; the resistance of this length of the liquid column is evidently equal to that added in the resistance-box. Repeat these observation two or three times. Enter your results thus:—

Liquid.	Cross-section of tube (πr^2).	Length of Liquid Column (l).	Resistance added (R).	$\frac{R \times \pi r^2}{l}$
		1		
		2		
		3		

Additional Exercises

1. Determine the specific resistance of copper and of iron.

2. Determine the specific resistance of the following solutions:—

(i.) Saturated solution of copper sulphate.
(ii.) Sulphuric acid (5 per cent solution).
(iii.) Saturated solution of ammonium chloride.

3. A wire is bent into the form of a circle (50 cms. radius), and the circle is marked off into four equal parts at the points A, B, C, and D. The points B and D are connected by a straight wire of the same material and diameter as that of the circle. If 1 metre of the wire has a resistance of one ohm, compare the resistance between A and C with that between B and D.

4. A glass tube, 1 metre long and 1 millimetre in diameter is filled with mercury. If the specific resistance of mercury is 94.3 microhms, find the resistance of the mercury thread.

5. The resistance of a reel of wire is 75 ohms. Two metres of the wire are cut off, and the resistance of this portion is found to be 0.25 ohm. What was the total length of wire on the reel?

6. You are supplied with wire having a diameter of .04 cm. and a specific resistance of 47.5 microhms. What length of the wire will be required in order to make a 10-ohm resistance coil?

7. A compass-needle is placed at the centre of two concentric circles which are in the same vertical plane, and are made of wires similar in all respects except that the outer is copper, the inner German silver. The wires are connected in multiple arc, but so that the currents which flow through them circulate in opposite directions. What must be the ratio of the diameters of the circles that no effect may be produced on the needle? (N.B.—Assume the conductivity of copper to be twelve times that of German silver). (1891.)

CHAPTER XX

THE POTENTIOMETER. ELECTROMOTIVE FORCE AND INTERNAL RESISTANCE OF CELLS. GROUPING OF CELLS

The potentiometer simply consists of a long uniform wire along which a steady current may be sent, and along which the fall of potential is uniform. It has already been used in Expt. 92 (p. 141), in which a measure of the E.M.F. of a standard cell is obtained by balancing its E.M.F. against an opposite potential difference derived from the long wire. In Fig. 82 the length of the wire between the points of contact (A and C) is a measure of the E.M.F. of the cell E_2. If another cell is substituted for E_2, and if the length of wire required to neutralise its E.M.F. is determined, then the ratio of the E.M.F. of the two cells is numerically equal to the ratio of the length of wire in the two observations.

103. Comparison of E.M.F. of Cells (Potentiometer Method)

Apparatus required.—Same as in Expt. 92. Daniell, Leclanché, Bunsen, Dry Cell, Accumulator, etc.

(i.) Connect up the apparatus as in Fig. 82. Frequently observe the deflection in the tangent galvanometer, and keep it constant by adjusting R (if necessary). Note the length of wire AC required to balance the E.M.F. of each cell when placed successively in the shunt circuit (see p. 140). Enter your observations in the following manner :—

Type of Cell.	Deflection in Galvanometer.	Length of Wire (AC).
1. Daniell		$l_1 =$
2. Leclanché		$l_2 =$
3.		
4.		

Express the E.M.F. of each cell in terms of that of the Daniell thus—

$$\frac{\text{Leclanché}}{\text{Daniell}} = \frac{l_2}{l_1} =$$

104. Fall of Potential at the Terminals of a Cell when the Circuit is closed. Internal Resistance of Cells (Potentiometer Method).

As a general rule the equation $C = \frac{E}{R}$ is applied to the entire *circuit* traversed by the current, including the battery as well as the external wires, both of which offer a resistance to the passage of the current. Hence, the symbol R includes both the resistance of the wire (usually termed the *external resistance*) and also that of the battery (usually termed the *internal resistance*). It is better to represent these component resistances by separate symbols, and to write the equation thus—

$$C = \frac{E}{R + r}, \quad . \quad . \quad . \quad (1)$$

where R = the external resistance, and r = the internal resistance. Since the battery has resistance, a portion of its E.M.F. will be used up in driving the current through the battery, and only the remainder of the total E.M.F. will be available for driving the current through the wire. This is rendered more evident by writing the above equation thus—

E	$=$	CR	$+$	$Cr.$	(2)
(Total E.M.F.)		(E.M.F. used in external circuit.)		(E.M.F. used in internal circuit.)	

This is represented diagrammatically in Fig. 93, where AB represents the internal resistance and BC the external resistance. AE is the total E.M.F., and Ee is the portion used up in overcoming the resistance of the cell, while BE′ represents the difference of potential between the ends of the wire.

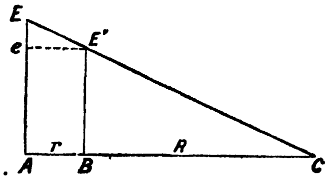


FIG. 93.

Equation (2) may be written—

$$E = e_1 + e_2.$$

The relative values of E and e_1 may be determined by means of the potentiometer, and the relative value of e_2 can then be obtained by difference.

Since $\dfrac{e_1}{e_2} = \dfrac{CR}{Cr} = \dfrac{R}{r}$; if the value of R is known, the internal resistance (r) of the cell can be determined.

(i.) **Daniell Cell.**—Measure the E.M.F. (expressed in cms. length of the potentiometer wire) of the cell on open circuit, by means of the potentiometer. Connect the poles of the cell through a resistance (R) of 10 ohms, and again measure the E.M.F. (e_1) at the terminals. Break the circuit, and again measure the E.M.F. in open circuit. Carefully note whether the total E.M.F. is the same as at the beginning of the experiment. Enter your results thus :—

Total E.M.F. (E).	Resistance (R).	E.M.F. in Closed Circuit (e_1).	$r = R \times \dfrac{(E - e_1)}{e_1}$.

(ii.) **Leclanché Cell.**—Repeat Expt. (i.) with a Leclanché cell, and carefully note that the total E.M.F. is considerably reduced immediately after the terminals have been short-circuited through a 10-ohm resistance. Determine the total E.M.F. at the end of every minute, in order to see how rapidly the cell recovers its original E.M.F. This temporary loss of E.M.F. is due to *polarisation* (see p. 111), and indicates one of the chief disadvantages of the Leclanché cell. This rapid loss of E.M.F., on being short-circuited, will of course render the determination of e_1 and of r untrustworthy.

105. Calibration of a Voltmeter (Low reading)

Apparatus required.—Potentiometer, etc. Voltmeter (reading 0-5 volts).

A voltmeter is exactly the same in principle as a galvanometer, except that the coil consists of a long wire of high resistance. If the terminals of the instrument are connected to any points of a closed circuit the extremely weak current which flows through the shunt circuit thus established will be proportional to the potential difference between the terminals. The scale attached to the instrument is usually calibrated in *volts*.

(i.) Arrange the potentiometer, etc., as shown in Fig. 82, and connect the + ve terminal of the voltmeter to that end of the potentiometer wire which is at higher potential. Maintain a *constant* current through the potentiometer during the experiment. Make contact between the – ve terminal of the voltmeter and a series of equidistant points on the potentiometer. Note in each case the length of wire and the corresponding reading of the voltmeter. Enter your results thus :—

Length of Potentiometer Wire.	Reading of Voltmeter.
200	0.70
300	1.10
400	1.42
500	1.80
700	2.52
900	3.40

Plot out these readings on squared paper, with the lengths of wire as abscissae and voltmeter readings as ordinates.

106. Comparison of the E.M.F. of Voltaic Cells (Direct Deflection Method)

Apparatus required.—Various cells. Mirror galvanometer. High resistance. Commutator.

The current generated in a simple circuit (consisting of a high resistance and a mirror galvanometer) is, by Ohm's law, proportional to the E.M.F. of the cell. The E.M.F. of different types of cell may be compared by inserting them successively in such a circuit, and comparing the current generated in each case. If the circuit includes a high resistance the internal resistance of the cells may be neglected; and if a sensitive mirror galvanometer is used the deflections observed may be regarded as proportional to the current passing through the instrument.

(i.) Connect in series the galvanometer, high resistance, commutator, and one of the cells supplied. Adjust the high resistance until a moderate deflection is observed. Carefully note the deflection. Reverse the current, and again note the deflection. Calculate the mean deflection. Repeat the observations with other types of cell. Enter your observations in the following manner:—

Type of Cell.	Deflection.		Mean Deflection.
	Left.	Right.	
i. Daniell			
ii. Leclanché			

Calculate the E.M.F. of the cells in terms of that of the Daniell.

107. *Voltmeters

The function of the galvanometer in the previous experiment suggests the principle of several types of *voltmeter* (or instrument for measuring differences of electrical pressure between any pair of points in a closed circuit). Such instruments are constructed either with a magnet suspended within a fixed coil of high resistance, or with a coil of high resistance suspended within a permanent magnetic field. The scale of the instruments is calibrated in volts. It is essential that the coil should in either case have a high resistance, in order that when connected to any points in a closed circuit it shall not interfere, to any measurable extent, with the distribution of current in the main circuit; in fact, the voltmeter forms a *high* resistance shunt to the main circuit, and the current traversing the shunt is, though so small, nevertheless proportional to the potential difference between its ends.

108. Comparison of the E.M.F. of Voltaic Cells (Method of Sum and Difference)

Apparatus required. Various types of cells (including a Daniell cell). Tangent galvanometer.* Commutator. Resistance (10 or 20 ohms).

If two cells (E.M.F. denoted by E_1 and E_2) are connected in series with a tangent galvanometer, then tan α is proportional to $(E_1 + E_2)$. If E_2 is then reversed, *tan* α will be less than before, and will be proportional to $E_1 - E_2$, (assuming that E_1 is greater than E_2). Hence

$$\frac{\tan \alpha_1}{\tan \alpha_2} = \frac{E_1 + E_2}{E_1 - E_2},$$

or,

$$\frac{E_1}{E_2} = \frac{\tan \alpha_1 + \tan \alpha_2}{\tan \alpha_1 - \tan \alpha_2}. \qquad (1)$$

(i.) Connect up the Daniell cell (E.M.F. $= E_2$) with another cell (E.M.F. $= E_1$) in series, with a commutator, resistance, and

* A tangent galvanometer will be sufficiently sensitive for this experiment if the E.M.F. of the cells differ by about 20 per cent; otherwise it is better to use a mirror galvanometer and a high resistance.

tangent galvanometer. Note the deflection of both ends of the needle, and also when the current is reversed. Reverse the cell having the lower E.M.F., and repeat the observations. Enter your results thus :—

Comparison of Leclanché (E_1) *and Daniell* (E_2)

Cells.	Deflections.		Mean Deflection (a).	tan a.
	East End.	West End.		
In conjunction ($E_1 + E_2$)	(i.)		$a_1 =$	tan $a_1 =$
	(ii.)			
In opposition ($E_1 - E_2$)	(i.)		$a_2 =$	tan $a_2 =$
	(ii.)			

Calculate the value of the ratio $\frac{E_1}{E_2}$ by means of equation (1).

109. Internal Resistance of Voltaic Cells (Tangent Galvanometer Method)

Apparatus required.—Battery of cells (three Leclanché cells are convenient). Box of known resistances. Tangent galvanometer (of known resistance). Commutator.

By Ohm's law, $R = \frac{E}{C} = \frac{E}{k \tan \theta}$ (where k = constant of galvanometer, and θ = angle of deflection); hence R (the *total* resistance) is proportional to $\frac{1}{\tan \theta}$. If different values of the *external* resistance, together with the corresponding values of $\frac{1}{\tan \theta}$, are plotted out on squared paper, the various points will be found to be on a straight line (Fig. 94), but this line intersects the horizontal axis at O′, and does not pass through the point of intersection (O) of the axes.

This is due apparently to the fact that no allowance has been made for the *internal* resistance of the cells; the distance OO′ is a measure of this internal resistance, which should have been added to the external resistance in order to give the total resistance.

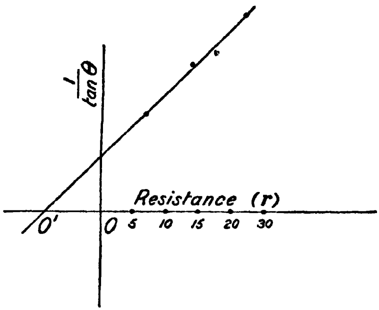


FIG. 94.

(i.) Connect up the battery, commutator, galvanometer, and resistance-box in series, and adjust the external resistance so that a convenient deflection is obtained. Note the external resistance, and the deflection obtained. Repeat, with the current reversed. Take at least three separate observations, with different resistances in the external circuit. Enter your results thus:—

Battery used = three Leclanché cells (in series).
Resistance of galvanometer =

Resistance in Box.	Total External Resistance (r).	Deflection.		Mean Deflection (θ).	$\frac{1}{\tan\theta}$.
		East End.	West End.		

Plot out these observations on squared paper, taking the external resistance (r) as abscissae, and $\frac{1}{\tan\theta}$ as ordinates.

Calculate the resistance of a single cell.

110. Grouping of Cells

Apparatus required.—Three Leclanché cells. Resistances of 5 ohms and 100 ohms. Tangent galvanometer. Commutator.

If n cells are connected together in series, and if E and r are the E.M.F. and internal resistance of one cell, then

$$C = \frac{nE}{R + nr} \quad . \quad . \quad . \quad . \quad (1)$$

If the cells are connected together in parallel, the E.M.F. will be the same as that of one cell; the arrangement will be equivalent to one large cell, the plates of which are n times as large as those of a single cell. Hence the total internal resistance $= \frac{r}{n}$, and

$$C = \frac{E}{R + \frac{r}{n}} \quad . \quad . \quad . \quad . \quad (2)$$

It is clear, from equation (1), when r is small compared with R, that the current obtained is approximately proportional to the number of cells used. But if R is small compared with r, then the current is scarcely increased by an increase in the number of cells, since the total resistance $(R + nr)$ will be increased almost in the same proportion as the E.M.F.; in this case it is advantageous to connect the cells in multiple arc so as to reduce the internal resistance, as represented in equation (2).

(i.) Connect up in series one Leclanché cell, a resistance of 100 ohms, the commutator, and a tangent galvanometer. Note the deflection. Repeat with two cells in series, with three cells in series, and with three cells in parallel.

Repeat these observations, but use a 5-ohm resistance instead of the 100-ohm resistance. Enter your observations in the following manner:—

Leclanche Cells.	Resistance of Coil.	Deflection.		Mean Deflection (a).	tan a.
		East End.	West End.		
1 cell	5 ohms				
2 cells in series	,,				
3 cells in series	,,				
3 cells in parallel	,,				

Note which arrangement of cells gives a maximum current through the low resistance, and through the high resistance.

110 b. The Use of Shunts

Apparatus required.—Mirror galvanometer. High resistance (10 to 20 megohms). Voltaic cell. Box of resistances.

It has been shown, on p. 155, that when two conductors, of resistance r_1 and r_2, are arranged in multiple arc, their combined resistance is equal to $\frac{r_1 r_2}{r_1 + r_2}$, and the current divides into two portions, c_1 and c_2, such that $\frac{c_1}{c_2} = \frac{r_2}{r_1}$.

This principle is often adopted in order to reduce the sensibility of a galvanometer, by connecting the coil of the instrument in multiple arc with a separate coil of known resistance (termed the *Shunt*).

If R_g and R_s are the resistances of the galvanometer and shunt respectively, and C_g and C_s the corresponding currents, then

$$\frac{C_s}{C_g} = \frac{R_g}{R_s},$$

or,

$$\frac{C_s + C_g}{C_g} = \frac{R_s + R_g}{R_s},$$

or,

$$\frac{C_g}{C_s + C_g} = \frac{R_s}{R_s + R_g}$$

But $(C_s + C_g)$ constitutes the *total* current traversing the circuit, hence the fraction of the current traversing the galvanometer is equal to $\frac{R_s}{R_s + R_g}$.

In order that the total current traversing the circuit may remain practically constant, however much the shunt may be altered, it is necessary that the total resistance in the circuit be very great compared with that of the galvanometer and shunt.

(i.) Measure the resistance of the galvanometer, if this has not previously been determined. Connect up the apparatus as shown in Fig. 95. K_1 and K_2 represent plug-keys, which though convenient, are not essential. R is a high resistance of 10 to 20 megohms, and S is the *Shunt*. Observe the zero scale reading. Complete the circuit, and adjust R so that a considerable deflection is obtained; enter the deflection in your note-book. Keep R constant during the experiment. Insert S into the circuit, make its resistance about equal to that of G, and again note the deflection. Repeat the observations with different values of S. Enter your results thus:—

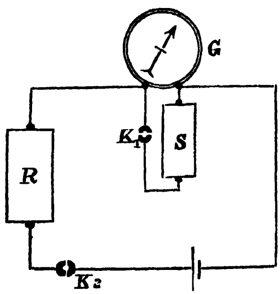


FIG. 95.

Resistance of galvanometer $(R_g) = 124$ ohms.
Deflection (δ_1), when shunt is not included, $= 236$ mms.

R_s.	Deflection (δ_2).	$\frac{R_s}{R_g+R_s}$.	$\frac{\delta_2}{\delta_1}$.
200 ohms	145	0.617	0.614
150 ,,	129	0.547	0.546
100 ,,	105	0.446	0.445
50 ,,	68	0.287	0.288
20 ,,	32	0.138	0.135

Hence, the fraction of the total current which passes through the galvanometer, is equal to the ratio of the resistance of the shunt to the sum of the resistances of the galvanometer and shunt.

Additional Exercises

1. Two cells, A and B (E.M.F. and internal resistance of each are one volt and one ohm respectively), are arranged in series. The positive and negative poles of this battery are connected with the positive and negative poles respectively of a third cell C, exactly like A and B, the connecting wires having negligible resistance. What is the current in the circuit, and what is the potential difference between the positive and negative poles of the cell C? (1891.)

2. The positive poles A and B of a Grove and a Daniell cell are joined by a wire of 0.3-ohm resistance, and the negative poles C and D by a wire of 0.5 ohm. What is the difference of potential between the middle points of AB and CD?

Grove cell:—Int. resistance = 0.2 ohm, E.M.F. = 1.8 volt.

Daniell cell:—Int. resistance = 0.4 ohm, E.M.F. = 1.1 volt. (1898.)

3. A circuit is formed of six similar cells in series and a wire of 10 ohms resistance. The E.M.F. of each cell is one volt and its internal resistance five ohms. Determine the difference of potential between the positive and negative poles of any one of the cells. (1894.)

4. Two cells, the E.M.F.'s of which are as 2 : 1, are joined up in series with their E.M.F.'s acting in the same direction, and the circuit is completed through a tangent galvanometer, the needle of which is deflected through 60°. If one of the cells is reversed, no other change being made, what will be the deflection of the galvanometer? (1896.)

5. A galvanometer, the resistance of which is $\frac{1}{3}$ ohm, being joined up in circuit with a cell by thick copper wires, the resulting current is noted; and it is found that the current in the galvanometer is halved if, without any other change being

made, the terminals of the galvanometer are joined by a wire of resistance 0.1 ohm. What is the resistance of the cell? (1893.)

6. A coil of known resistance and a length of wire (of unknown resistance) are connected in series to the terminals of a voltaic cell. By means of the potentiometer and a sensitive galvanometer, determine the resistance of the length of wire.

7. Determine the resistance of a short length of thick copper wire by the same method as described in Question 6.

CHAPTER XXI

Thermal and Chemical Effects

111. Thermal Effects—Preliminary Experiments

Apparatus required.—Two large Bunsen cells (or accumulators). Thin platinum wire (No. 32). Thin copper wire. Thermometer.

(i.) **Heat generated in a Wire.**—Connect two large Bunsen cells in series. Connect the poles, by means of thick copper wires, to the ends of a short piece of platinum wire (No. 32 S.W.G.). Observe how the wire is heated, and perhaps even glows. If the wire is too long it will not glow, since the total resistance is too great to allow sufficient current for the experiment; the resistance may be reduced either by shortening the wire, or by reducing the resistance of a portion of the wire by immersing in a vessel of cold water, when the remaining portion will glow brightly.

Substitute thin copper wire for the platinum wire. Notice that the copper wire does not acquire the same high temperature as the platinum; it may become perceptibly hot, but not more than this.

(ii.) **Heat generated in the Voltaic Cell.**—Immerse a thermometer in the acid of one of the cells, and read the temperature of the liquid. Connect the poles by means of a short thick wire, and allow the current to continue for a short time. Observe how the temperature of the acid gradually rises.

112. Joule's Law

Apparatus required.—Two calorimeters fitted with spirals of wire (see note 33, p. 228). Two large Bunsen cells (or

accumulators). Tangent galvanometer (low resistance). Commutator. Adjustable resistance.

Joule's Law may be stated thus: *The heat generated in a simple circuit is proportional* (i.) *to the square of the current*, (ii.) *to the resistance*, (iii.) *to the time during which the current continues.* The general principle of the apparatus which Joule used in the experimental proof of this law may be understood by reference to Fig. 96. The ends of an open coil of thin German-silver wire are connected to thick copper wires passing through the cork of the calorimeter. The coil is immersed in water, and all the heat generated in the wire is utilised in raising the temperature of the water and calorimeter; the change in temperature can be observed by means of a thermometer.

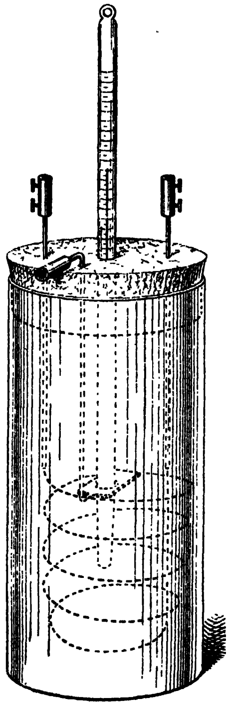


FIG. 96.—Apparatus for proving Joule's law.

(i.) **Heat generated is proportional to the Resistance and to the Time.**—Connect up, as shown in Fig. 97, the two spirals (R_1 and R_2), the adjustable resistance (R), the battery (B), the commutator (C), and the tangent galvanometer (T.G.). Adjust R, so as to obtain a suitable deflection of about 30°. Dry and weigh the calorimeters and pour equal weights of cold water into each of them, sufficient in quantity to cover the spirals. Note the reading of each thermometer. Note

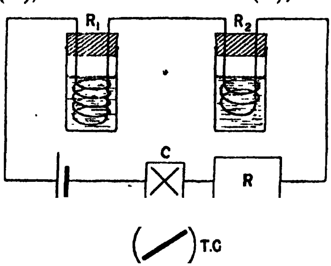


FIG. 97.

the time by your watch and immediately complete the circuit. During the experiment, frequently stir the water in each calorimeter by means of the stirrer passing through the corks; also carefully watch the galvanometer, and, if necessary, adjust R so as to keep the deflection constant. At the end of ten minutes note down the temperatures, quickly reverse the direction of the current, note the deflection, and continue the experiment for exactly ten minutes longer. Enter your results thus:—

$$\left.\begin{array}{l}\text{Resistance of } R_1 = \quad \text{ohms.} \\ \text{Resistance of } R_2 = \quad \text{ohms.}\end{array}\right\}$$

Time	Temperature of R_1	Temperature of R_2	Deflection.		Mean Deflection (a_1)	tan a_1.
			East End.	West End.		
10 h. 30′						
10 h. 40′						
10 h. 50′						

(A) $\dfrac{\text{Rise in temperature of } R_1 \text{ in 10 minutes}}{\text{Rise in temperature of } R_1 \text{ in 20 minutes}} =$

$$\frac{10 \text{ minutes}}{20 \text{ minutes}} =$$

The equality of these ratios proves that *the amount of heat generated by the current is proportional to the time.*

(B) $\dfrac{\text{Rise in temperature of } R_1 \text{ in 20 minutes}}{\text{Rise in temperature of } R_2 \text{ in 20 minutes}} =$

$$\frac{\text{Resistance of } R_1}{\text{Resistance of } R_2} =$$

The equality of these ratios proves that *the amount of heat generated is proportional to the resistance.*

(ii.) **Heat generated is proportional to the Square of the Current Strength.**—Remove R_1 from the circuit, and carry out the following experiment with R_2 :—Thoroughly dry the calorimeter and pour into it exactly the same weight of cold water as used in Expt. 112 (i.). Adjust R so as to obtain a greater deflection than before. Insert the spiral into the calorimeter and proceed exactly as in Expt. 112 (i.), taking special care to keep the deflection constant, and also reversing the current two or three times so as to obtain the true mean deflection. Enter your results thus :—

Time.	Temperature of R_2.	Deflection.		Mean Deflection (α_2).	tan α_2.
		East End.	West End.		
11 h. 0′					
11 h. 10′					
11 h. 20′					

Compare the rise in temperature in this experiment with that obtained in the same calorimeter in Expt. 112 (i.), and calculate the following ratios :—

$$\frac{\text{Rise in temperature in Expt. ii.}}{\text{Rise in temperature in Expt. i.}} =$$

$$\frac{(\tan \alpha_2)^2}{(\tan \alpha_1)^2} =$$

This result should verify the fact that the heat developed is proportional to the *square of the current.*

113. Practical Applications of the Thermal Effects of a Current

1. **Safety Fuses.**—The heat generated in a wire by a current is utilised for the purpose of protecting a conductor

from too strong a current. The usual method is to insert in the circuit a short piece of easily fusible wire (of lead or tin) of such a size that it will fuse before the current becomes dangerous to any other part of the circuit.

2. **Incandescent Lamps.**—The temperature of a carbon filament is raised to bright red heat by the passage of an electric current through the filament.

3. **Electric Welding.**—Two bars of metal may be joined by placing them in contact end to end, and passing a strong current across the junction. The point of contact, offering a comparatively high resistance, is locally heated to a sufficiently high temperature to weld the surfaces together.

4. **Blasting Fuses.**—These consist of a short piece of thin platinum wire, inserted in the base of the detonating charge, the ends of which are connected by long insulated wires to a distant battery. The charge is fired by passing a strong current through the platinum wire.

5. **Electric Cautery.**—In surgery, a short piece of platinum wire heated to redness by means of a current is frequently used for the purpose of cauterising animal tissue.

114. Chemical Effects—Preliminary Experiments

Apparatus required. — Bunsen cells (or accumulators). Platinum wire. Dilute sulphuric acid. Copper sulphate solution (10 per cent with 1 c.c. concentrated sulphuric acid added to each litre). Apparatus for electrolysis of water. (Fig. 98).

The passage of a current through *mercury* is similar in every respect to the passage of a current through a solid metal conductor—heat is developed in the mercury, but no other change is evident. But when the current traverses other liquids (*e.g.* acids, solutions of chemical salts, etc.) they undergo chemical change. *Liquids which undergo chemical change when traversed by an electric current are termed Electrolytes*, and they are said to undergo *Electrolysis.*

The ends of the wires connected to the battery are termed *electrodes;* that by which the current enters the electrolyte is termed the *anode*, and that by which it leaves is termed

the *kathode*. The elements (or group of elements) liberated at the anode and kathode are termed the *anions* and *kations* respectively

(i.) **Electrolysis of Copper Sulphate.**—Connect two short lengths of platinum wire to copper wires attached to the poles of a battery. Dip the platinum wires into a solution of copper sulphate. Allow the current to pass for a few moments, and observe how the kathode becomes coated with a layer of copper; also note what takes place at the anode.

(ii.) **Electrolysis of Water.**—Nearly fill the funnel (Fig. 98) with dilute sulphuric acid; fill the test-tubes with a similar acid, and invert them over the platinum strips. Connect the copper wires to the terminals of a Bunsen battery (of at least two cells). Notice how the kation accumulates twice as rapidly as the anion. Break the circuit, and remove the test-tubes (carefully closing the ends with the thumb before removing them from the acid). Verify that the kation is hydrogen, and that the anion is oxygen.

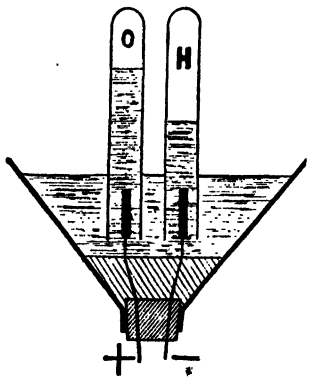


FIG. 98.—Apparatus for electrolysis of water.

The electrolysis of water may be represented thus :—

H_2O	=	H_2	+	O.
Water	is decomposed into	2 vols. *Hydrogen*	and	1 vol. *Oxygen.*

115. Faraday's Laws of Electrolysis

Apparatus required.—Battery of three large cells (or accumulators). Tangent galvanometer (low resistance). Commutator. Adjustable resistance. Copper voltameter (see note 34, p. 228). Water voltameter (see note 35, p. 228).

Faraday deduced the following laws :—(1) The amount of chemical action is equal at all points of a circuit. (2) The

quantity of an element liberated is proportional to the strength of the current and to the time during which it flows.

(i.) **The Weight of Copper deposited is Proportional to the Time.**—When using the copper voltameter (Fig. 99), the two outer plates should be joined together to form the *anode*, while the middle plate is the *kathode*. With this arrangement copper will be deposited on both sides of the kathode; also the increase in weight of the kathode during any experiment should equal the total loss in weight of the anodes.

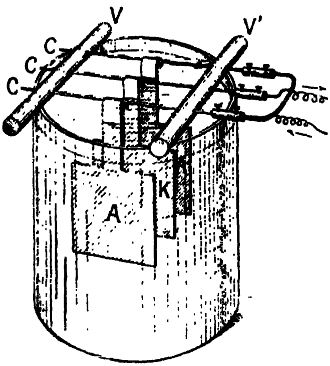


Fig. 99.—Copper voltameter.

Thoroughly clean the copper plates with sand-paper. Connect up the battery, voltameter (V), adjustable resistance (R), commutator (C), and tangent galvanometer (T.G.), as shown in Fig. 100. Adjust R until a convenient deflection is obtained. Break the circuit, remove the copper plates, wash them in water and dry them quickly over a spirit flame. Weigh the kathode, and also the two anodes. Replace the plates in position. Note the time by your watch at the instant when the circuit is closed. Frequently observe the deflection, and keep it constant by adjusting R; also, reverse the commutator occasionally so as to obtain the true deflection. At the end of fifteen minutes, break the circuit, remove the plates, wash them in water, dry them quickly over a flame, and weigh the kathode and also the anodes. Determine the increase in weight of the former and the loss in weight of the latter.

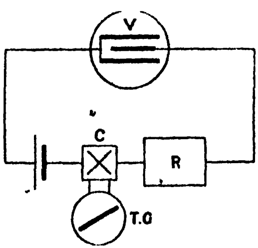


Fig. 100.

Repeat the experiment, using exactly the *same* current strength as before, and allow the deposition of copper to continue for exactly thirty minutes.

Enter your results thus: -

Duration of Experiment.	Increase in Weight of Kathode.	Loss in Weight of Anode.	Deflection.		Mean Deflection.
			East End.	West End.	
15 minutes.					
30 ,,					

(ii.) **The Volume of Mixed Gases liberated from a Water Voltameter in a Given Time is Proportional to the Current Strength.**—Connect up the voltameter (Fig. 101), battery, galvanometer, etc., as shown in Fig. 100. Complete the circuit and allow the chemical action to proceed, adjusting the resistance (R) so that a deflection of 20°–25° is obtained. Keep the circuit closed during the whole of the experiment. Nearly fill the burette with water, close it with the thumb, and invert the burette so as to ensure that the level of the water can be read directly on the graduated scale.

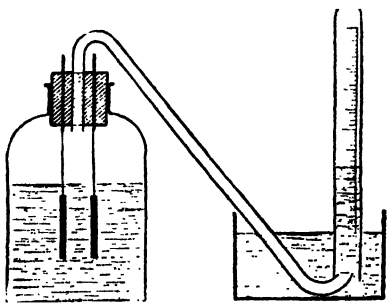


FIG. 101.—Water voltameter.

In the experiment, the volume of mixed gases liberated is obtained by collecting them in the burette, observing the *total* volume of gas in the burette, and from this total subtracting the volume of air which was in the burette at the commencement of the experiment. *Both volumes must be measured under the same conditions of temperature and pressure:* this is

done by closing the burette with the thumb, inverting it, and immersing it in water contained in a deep glass cylinder, until the level of the water inside and outside the burette is the same. The enclosed gas is then at atmospheric pressure, and its volume may be read, after leaving the burette immersed in the water for two or three minutes so as to acquire the same temperature as that of the surrounding water.

Now transfer the burette to the glass trough, and at an observed moment (by your watch) place the burette over the leading tube from the voltameter. Carefully watch the deflection, and keep it constant by means of the resistance (R). During the experiment rapidly reverse the current in the galvanometer by reversing the commutator as rapidly as possible, and note the deflection. When eight or ten minutes have elapsed, remove the burette from over the leading tube, noting the exact time at this moment. Read the total volume of gases in the manner already described.

Reduce the resistance (R) until a deflection of 30° or 35° is obtained. Repeat the previous experiment, *allowing the current to continue for exactly the same time interval.* Enter your results thus :—

Initial Burette Reading.	Final Burette Reading.	Volume of Mixed Gases (V).	Mean Deflection (α)	tan α.
1				
2				

$$\text{Ratio of volumes of mixed gases, } \frac{V_1}{V_2} = \quad .$$

$$\text{,, current strengths, } \frac{\tan \alpha_1}{\tan \alpha_2} = \quad .$$

(iii.) The Amount of Chemical Action is equal at all Points of a Circuit.—An experiment to prove this law may be

arranged by inserting two copper voltameters in circuit, one on either side of the battery, and comparing the weight of copper deposited in the two voltameters.

116. Electro-chemical Equivalents

It has been found that a current of one ampere will, in one second, deposit .000328 gm. of copper; this is called the *electro-chemical equivalent* of copper. The electro-chemical equivalent of other elements can be calculated from this, since the weight of elements deposited by the same current in the same time is directly proportional to their *chemical equivalents* (*i.e.* the weights of the element which will combine with, or replace, one gram of hydrogen).

The chemical equivalent of copper is 31.59 (when that of hydrogen is 1). Hence the weight of hydrogen liberated by one ampere in one second $= \frac{.000328}{31.59} = 0.0000104$ gram; this weight of hydrogen will occupy 0.1155 c.c., measured at 0° C. and 760 mm. pressure. The volume of oxygen liberated, under the same conditions, is 0.0577 c.c.

Hence, in the water voltameter, in which the *mixed* gases are collected, one ampere will liberate 0.1732 c.c. of the gases in one second.

By means of these data the strength of a current may be determined either by measuring the weight of copper deposited, or the volume of mixed gases liberated in a given interval of time: thus, in the case of a copper voltameter,

Weight deposited = Electro-chem. equivalent × current × time.

117. Industrial Applications of the Chemical Action of an Electric Current

Electro-plating is a term which denotes the deposition of a thin layer of a metal on any object by means of an electric current. The metals which are most frequently deposited in this manner are copper, silver, nickel, and gold. The objects to be plated are thoroughly cleaned, and then suspended from copper wires in a liquid bath (containing in solution a salt of

the metal which is to be deposited); the copper wires form the kathode, and a plate of the metal to be deposited forms the anode. The solution used in copper-plating contains copper sulphate, and is rendered slightly acid by the addition of sulphuric acid; that used in nickel-plating contains nickel-ammonium sulphate and ammonium sulphate. Silver is deposited from a solution of the double cyanide of silver and potassium; and gold is deposited from the double cyanide of gold and potassium.

Electro-typing is the process by which the surface of any object is coated with a layer of copper sufficiently thick to allow it to be subsequently removed and used as a copy of the original object. The surface of the object is coated with black-lead in order to make the surface a conductor. Coins and medals may be reproduced by taking a plaster cast of the coin; the face of the cast is then coated with black-lead, and copper is deposited on the conducting surface. Printer's type and wood engravings may be reproduced by taking a cast in wax or in papier-mâché, and obtaining a copper reproduction which is afterwards strengthened by being backed with a thick layer of type-metal.

Electro-metallurgy includes the manufacture on a large scale of aluminium, which is obtained by the electrolysis of fused oxide of aluminium. The oxide is contained in a large iron vessel, which forms the kathode in the circuit; the anode consists of several stout carbon rods. Oxygen is liberated at the anode and combines with the carbon to form carbon monoxide; the aluminium gradually accumulates in the bottom of the iron vessel. The metals sodium and potassium were discovered by Davy, who separated the metals from the fused hydrate by means of electrolysis.

ADDITIONAL EXERCISES

1. Part of the circuit of an electric current consists of a bare wire which passes through a vertical glass tube corked at the lower end. Explain the effect on the temperature of the wire and on the current in the circuit of gradually filling the tube with mercury. (1897.)

2. Explain the term *electro-chemical equivalent.* If 3 amperes deposit 4 grammes of silver in twenty minutes, what is the electro-chemical equivalent of silver? (1899.)

3. A current is sent through three electrolytic cells, the first containing acidulated water, the second sulphate of copper, the third contains a solution of silver in cyanide of potassium. How much copper will have been deposited in the second cell, while 2.268 grammes of silver have been deposited in the third cell? And what volume of mixed gases will have been given off at the same time in the first cell? (Evening Exhibitions, L.C.C., 1900.)

4. A dynamo is capable of depositing 4 kilograms of copper in one hour. What is the strength of current generated by the dynamo?

CHAPTER XXII

THE CONSTANT OF A TANGENT GALVANOMETER

The *constant* (K) of a tangent galvanometer is the numerical quantity by which *tan* α must be multiplied in order to give the strength of the current in amperes; or,

$$C = K \tan \alpha.$$

K may be determined by either of four methods: (i.) By calculation from the radius of the coil and the number of turns of wire contained in it, and from the value of the horizontal intensity of the earth's field at the place where the instrument is situated. (ii.) By the electrolytic deposition of copper. (iii.) By the volume of gases liberated when water is electrolysed. (iv.) By the heat generated in a given time in a wire of known resistance.

118. The Constant of a Galvanometer calculated from its Dimensions

In § 87 it has been shown that the deflecting force in the tangent galvanometer is $\frac{C \times 2\pi n \times m}{r}$ (when C = the current in electromagnetic units, n = the number of turns of wire, m = the pole strength of the needle, and r = the radius of the coils), also that the controlling force is Hm (where H = the horizontal intensity).

If the current is measured in *amperes*, then the deflecting force is $\frac{C \times 2\pi n \times m}{10r}$ (since 1 ampere $= \frac{1}{10} \times$ electromagnetic unit of current).

$$\tan a = \frac{\text{deflecting force}}{\text{controlling force}} = \frac{C \times 2\pi n \times m}{10r} \Big/ H \times m = \frac{C \times 2\pi n}{10Hr}.$$

But $\tan a = \frac{C}{K}$.

Hence $$\frac{C \times 2\pi n}{10Hr} = \frac{C}{K},$$

or, $$K = \frac{10Hr}{2\pi n}.$$

(i.) It is necessary to know the horizontal intensity (H) of the earth's field at the point where the galvanometer is situated, the radius of the coil (r), and the number of turns (n) of wire in the coil.

If the value of H has not been determined accurately it will usually suffice to take $H = 0.18$; but, in this case, the space surrounding the instrument must be free from iron pipes or girders, and also from any bar-magnets, since these disturbing influences might considerably alter the value of H. The values of n and r can only be obtained during the making of the instrument. Note down your measurements thus:—

Inner circumference of coil ($2\pi r$) = 78.19 cms.
Inner radius (r) = 12.45 cms.
Radius of wire (r_1) = 0.07 cms.
Mean radius of coil 12.52 cms.
Number of turns of wire = 4

$$K = \frac{10Hr}{2\pi n} = \frac{10 \times .18 \times 12.52}{6.283 \times 4} = 0.897.$$

119. Galvanometer Constant, by the Weight of Copper Deposited

The method depends upon the fact that a current of one ampere will deposit 0.000328 gm. of copper in one second.

If t = duration of experiment in seconds,
W = weight of copper deposited,
C = current in amperes,

then $$C = \frac{W}{0.000328 \times t} \text{ amperes,}$$

or, $$K = \frac{W}{0.000328 \times t \times \tan a}.$$

(i.) Conduct the experiment exactly as described on p. 180, allowing the current to continue for about forty-five minutes. Enter your observations thus :—

Time.	Weight of Cathode.	Deflection.		Mean Deflection.
		East End.	West End	
Initial 11 h. 32′	13.642 grams.	21°.5	23°.9	22°.4
Final 12 h. 32′	14.1254 grams.	23°.1	21°.1	

Weight of copper deposited (W) = 0.4834 grams.
Duration of experiment (t) = 3600 seconds

$$K = \frac{0.4834}{0.000328 \times 3600 \times \tan 22^\circ.4} = 0.9934.$$

120. Galvanometer Constant, by the Electrolysis of Water

The method depends upon the fact that a current of one ampere liberates 0.1734 c.c. of mixed gases in one second. Since this volume of gas is measured at 0°C, while the gas liberated in the experiment is measured at the temperature of the room, it is necessary to calculate what this latter volume of gas would be if measured at 0°C.* Since the volume occupied by a gas is proportional to (273 + its temperature in degrees Centigrade), then—

$$\frac{\text{Volume at } 0^\circ\text{C.}}{\text{,, ,, } t^\circ\text{C}} = \frac{273}{273+t},$$

or,

$$\text{Volume at } 0^\circ\text{C } (V_0) = V_t \times \frac{273}{273+t}.$$

* When considerable accuracy is required, it is also necessary to correct the volume of gas to normal pressure (760 mms. of mercury), since the volume 0.1734 c.c. is measured at this pressure. The volume of a gas varies inversely as the pressure ; hence if the height of the barometer $= h$ mms., the complete correction would be $V = V_t \times \frac{h}{760} \times \frac{273}{273+t}$.

If t = duration of the experiment in seconds
V_0 = volume of gas liberated (corrected for temperature)
C = current in amperes

then $C = \dfrac{V_0}{0.1734 \times \text{time}}$,

and $K = \dfrac{V_0}{0.1734 \times \text{time} \times \tan \alpha}$.

(i.) Conduct the experiment exactly as described on p. 181. Enter your results thus:—

Time.	Burette Reading.	Temperature of Water.	Deflection.		Mean Deflection (α).
			East End.	West End.	
Initial, 11h. 10′	48.7 c.c.	14°.6	17°.9	18°.3	18°.17
Final, 11h. 23′	2.7 c.c.		18°.2	18°.4	

Volume of gas at 14°.8 (V_t) = 46 c.c.

" " " 0° C (V_0) $= \dfrac{46 \times 273}{287.6} = 43.67$ c.c.

$$K = \frac{43.67}{0.1734 \times 780 \times \tan 18^\circ.17} = 0.984.$$

121. Galvanometer Constant, by the Heat generated in a Wire of Known Resistance

Unit potential difference exists between two points when an expenditure of unit work is required in order to convey unit quantity of electricity between the two points. If the unit quantity is forcibly conveyed from lower to higher potential (*i.e.* in opposition to the electric forces) the work has to be done by some external agency; but if it proceeds in the opposite direction (*i.e.* in obedience to the electric forces), then unit work will be done *by* the electric forces. In a simple electrical circuit this work reappears in the form of *heat*.

If Q *coulombs* traverse a wire, between the ends of which there is a potential difference of E *volts*, then the work done $=(Q \times E)$ practical units. Or, since Q = current (C) × time (t), the work done $= ECt = C^2Rt$.

In order to express the work done in absolute units (*ergs*), it must be remembered that C amperes $= \frac{C}{10}$ absolute units, and that R ohms $= (R \times 10^9)$ absolute units of resistance.

$$\text{Hence, work done} = \left(\frac{C}{10}\right)^2 \times (R \times 10^9) \times t \text{ ergs.}$$

$$= C^2Rt \times 10^7 \text{ ergs.} \qquad . \quad . \quad . \text{ (i.)}$$

The number of heat units* generated in the wire can be measured by means of the apparatus shown in Fig. 96, (p. 175). The total heat units (H) generated = Heat absorbed by the water + Heat absorbed by calorimeter and stirrer.

If W = weight of water
w = weight of calorimeter and stirrer
s = specific heat of copper
T_1 = the initial temperature
T_2 = the final temperature

then $H = W(T_2 - T_1) + ws(T_2 - T_1) = (W + ws)\ (T_2 - T_1)$ heat units.

By elaborate experiments Joule determined that the work equivalent to one heat unit $= (4.2 \times 10^7)$ ergs.

$$\text{Hence } H = (W + ws)\ (T_2 - T_1)\ (4.2 \times 10^7) \text{ ergs.} \qquad \text{(ii.)}$$

By equating the expressions (i.) and (ii.)

$$C^2Rt \times 10^7 = (T_2 - T_1)\ (W + ws) \times (4.2 \times 10^7).$$

$$\text{or } C = \sqrt{\frac{(T_2 - T_1)(W + ws) \times 4.2}{Rt}} \text{ amperes.}$$

But $C = K \tan a$.

$$\text{Hence } K = \frac{1}{\tan a} \sqrt{\frac{(T_2 - T_1)(W + ws) \times 4.2}{Rt}} \qquad \text{(iii.)}$$

(i.) Measure the resistance of the spiral (Fig. 96) by the

* One heat unit (*therm.*, or, *calorie*) is the amount of heat required to raise the temperature of one gram. of water through 1° C.

Wheatstone bridge method (see p. 149). Clean, dry, and weigh the copper calorimeter and stirrer (without the cork, thermometer and spiral). Pour into the calorimeter enough cold water to cover the spiral, and again weigh. Connect up the spiral, galvanometer (low resistance coil), etc., as shown in Fig. 97. Complete the circuit for a short interval of time in order to adjust R until a deflection of about 40°-50° is obtained. Break the circuit, and stir the water in the calorimeter. Note the initial temperature. Complete the circuit, and note the time by your watch. Frequently stir the water, and allow a uniform current to continue until a rise in temperature of not less than 3° or 4° C. has been obtained. Quickly reverse the current, and note the deflection. Break the circuit and note the time. Enter your results thus :—

Resistance (R) of spiral = 21.24 ohms.
Weight of calorimeter and stirrer (w) = 57.95 grams.
Specific heat of copper (s) = 0.09.
Weight of water (W) = 182 grams.
Initial temperature (T_1) = 17° C.
Final temperature (T_2) = 20°.8 C.
Duration of experiment (t) = 1080 seconds.

$$C = \sqrt{\frac{(T_2 - T_1)(W + ws) \times 4.2}{Rt}} \text{ amperes} = 0.361 \text{ amperes.}$$

Current (C).	Deflection.		Mean Deflection (a).	Tan a.	$K = \frac{C}{\tan a}$.
	East End.	West End.			
0.361	20°.4 21°.0	19°.7 21°.1	20°.5	0.3739	0.965

ADDITIONAL EXERCISES

1. Pass the same current through a copper voltameter and a tangent galvanometer. Determine the strength of the

current by means of the voltameter (one ampere deposits .000329 grams of copper in one second). Deduce the current strength required to produce a deflection of 45° in the tangent galvanometer. (Int. County Schools, L.C.C., 1900.)

2. A constant current is sent, for thirty minutes, through a copper voltameter and a tangent galvanometer, the coil of which has a radius of 15 cms., and consists of three turns of wire. The mean deflection observed is 60°, and the weight of copper deposited in the voltameter is 1.6 gms. If the electro-chemical equivalent of copper is 0.000328, find the value of H.

3. A current of one ampere flowing for one second through a resistance of 1 ohm produces 0.239 gram-centigrade units of heat. What current would have to flow for an hour through a resistance of 41.84 ohms in order that the heat produced might suffice to raise a kilogram of water from 0° C. to the boiling point? (1897.)

4. A current from an accumulator is sent through the low resistance coil of a tangent galvanometer, and through a coil of wire of 0·5-ohm resistance which is immersed in 50 grams of water. The temperature of the water rose 11°.5 C. in thirty minutes. Calculate the strength of the current. If the mean deflection was 40°, find the constant of the galvanometer.

CHAPTER XXIII

SOLENOIDS. MAGNETIC SATURATION. ABSOLUTE E.M.F. OF STANDARD CELLS: EFFICIENCY OF LAMP

122. The Magnetic Action of Solenoids

Apparatus required.—Two long narrow solenoids of wire (not of the same gauge), (see note 36, p. 229). Magnetometer. Tangent galvanometer (low resistance). Commutator. Battery. Carbon rheostat.

It has already been shown (p. 121) that a solenoid, through which an electric current is passing, has magnetic properties similar to those of a bar-magnet. It can be proved by mathematical processes that the strength of the magnetic field in the neighbourhood of such a solenoid is proportional (i.) to the strength of the current traversing the solenoid, and (ii.) to the number of turns of wire per unit of length of the solenoid. These facts can be proved experimentally either by observing the changes in the deflection of a magnetometer needle (when the solenoid is placed with its axis to the east or west of the centre of the needle), or by determining the changes in the rate of vibration of a suspended magnet. In the following experiments the former method is adopted :—

(i.) **The Strength of the Field is Proportional to the Current.**—Adjust the magnetometer so that its scale is perpendicular to the magnetic meridian. Place one of the solenoids on the scale of the magnetometer in line with the centre of the needle, and with its near end about 10 cms. distant from the needle's centre. Connect the solenoid in series with the rheostat (R), the galvanometer (TG), and the commutator

(Fig. 102). The galvanometer must be placed at a considerable distance from the solenoid. Adjust R so that a slight

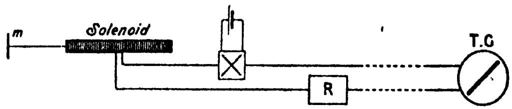


FIG. 102.—The magnetic action of solenoids.

deflection of the magnetometer needle is observed. Note the deflections of both the magnetometer and the galvanometer, reverse the current and repeat the observations. Repeat this, using stronger currents. Enter your results thus :—

Tangent Galvanometer.		Mean Deflection.	tan α.	Magnetometer.		Mean Deflection (θ).	tan θ.
East End.	West End.			East End.	West End.		

Plot out a curve on squared paper, taking values of *tan* α as ordinates and values of *tan* θ as abscissae. Note whether the curve obtained suggests any simple relationship between the current strength and the strength of the magnetic field due to the solenoid.

(ii.) **The Strength of the Field is proportional to the Number of Turns of Wire per Unit Length.**—Insert both solenoids into the circuit, arranged as in Fig. 102, using connecting wires of sufficient length to allow one solenoid to be placed at a distance while observations are being made with the other.

Count the total number of turns of wire in each solenoid, and also measure the total length of each solenoid. Calculate the number of turns of wire per cm. length. Place one of the

solenoids in position (as described in Expt. 122, i.), and observe the deflection of the magnetometer needle; repeat the observations with the current reversed. Substitute the second solenoid for the first one, and again repeat the observations. Enter your results thus:—

Number of turns per cm. length.	Deflection.		Mean Deflection (a).	tan a.
	East End.	West End.		
N_1 =				$\tan a_1$ =
N_2 =				$\tan a_2$ =

Calculate the following ratios:—(i.) $\frac{N_1}{N_2}$, (ii.) $\frac{\tan a_1}{\tan a_2}$.

If these ratios are equal, the experiment proves that the strength of the field is proportional to the number of turns of wire per unit length.

123. Magnetisation of Iron by means of an Electric Current

Apparatus required.—The same as in Expt. 122 (i.) Three or four pieces of soft iron wire (No. 22, 30 cms. long).

If a piece of soft iron is situated within a magnetic field, the iron becomes magnetised in the same direction as that of the lines of force of the field; also within certain limits, the degree of magnetisation depends upon the strength of the field. If, therefore, soft iron is placed inside a solenoid through which an electric current is passing, the iron will become magnetised. (It is upon this principle that *Electromagnets* are constructed.) If the current strength is gradually increased, the degree of magnetisation will also increase; but if the current is increased beyond a certain limit it will be found that the magnetisation of the iron ceases to increase; this indicates that the iron is *magnetically saturated*.

The curve AB (Fig. 103) indicates the relationship between

the current strength and the magnetisation of the iron while the current is being gradually increased; and the flatness of the curve near to B indicates the magnetic saturation. If the current is now slowly diminished (curve BC) it will be found,

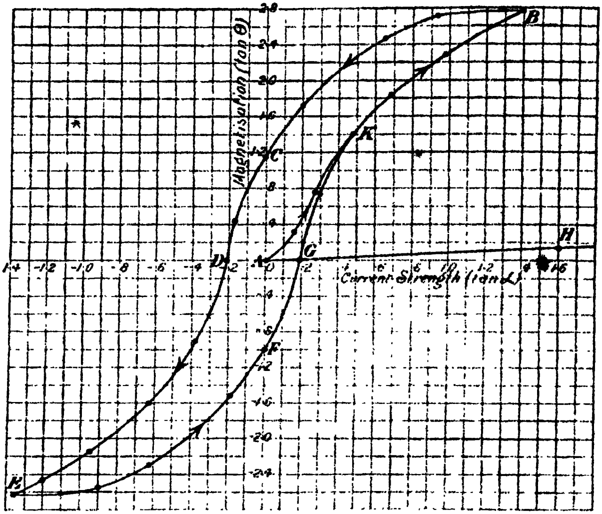


FIG. 103.—Cycle of changes in the magnetisation of iron by means of a solenoid.

for any definite current strength, that the degree of magnetisation is greater than when the current was increasing; also, when the circuit is broken, the magnetisation represented by the point C will still remain. If a weak current is sent through the solenoid in the reverse direction, and gradually increased, the iron will lose all its magnetisation (as shown at point D); with a further increase of current the curve DE will be obtained, the flatness at E indicating saturation with reversed polarity. If the current is now gradually diminished, the curve EF is obtained. The remainder (FGK) of the curve is obtained by again reversing the current to its original direction and gradually increasing its strength.

Evidently, in this cycle of operations, the magnetisation *lags* behind the current, and this behaviour on the part of the iron is termed *Hysteresis*. The area enclosed within the curved figure depends upon the quality of iron or steel used: soft iron gives a much smaller area than steel. The results of such an experiment afford important information as to the suitability of samples of iron in the construction of dynamos, etc.

(i.) Arrange the apparatus in the same manner as described in Expt. 122 (i.), and insert three lengths of soft iron wire into the solenoid (the length of each wire should be equal to that of the solenoid). Since the current may not be reversed at each reading, it is necessary, in order to obtain the true deflection, to note the *zero readings* of the pointers of both the magnetometer and the tangent galvanometer; enter these readings in your note-book as shown below, and subtract or add them, as the case may be, from all subsequent readings of deflection (§ 87, i.). Adjust R so that a very weak current traverses the circuit. Complete the circuit, and note the deflections of both instruments. *Do not tap the magnetometer or disturb it in any way.* Repeat these observations with increasing current, until a deflection of 60° or 70° is obtained in the tangent galvanometer. Continue the observations, diminishing the current at each step, and also when the circuit is broken. Now reverse the current, and proceed in exactly the same manner as before. Enter your observations thus:—

	Magnetometer.	Tangent Galvanometer.
Zero readings	East end—1.6 south	East end—0.2 north.
	West end—1.1 south	West end—1.4 south.

Magnetometer.		Mean Deflection (θ).	tan θ.	Tangent Galvanometer.		Mean Deflection (a).	tan a.
Readings.	Readings Corrected.			Readings.	Readings Corrected.		
25.2 N.	26.8	26.3	0.494	12.7 S.	12.9	13.0	0.231
27. S.	25.9			10.7 N.	13.1		

Plot out your observations on squared paper, as shown in Fig. 103.

The deflections of the magnetometer needle are, of course, due partly to the soft iron and partly to the solenoid itself, but the latter is very small as compared with the former. If it is desired to eliminate the effect of the solenoid, this may be done by removing the iron wire, replacing the solenoid in its original position, passing a strong current through it, and observing the deflections as described above. This observation is plotted on the squared paper, and connected to the origin of the axes by a straight line (AH, Fig. 103), which gives the value of $\tan\theta$, due to the solenoid alone, for all values of $\tan\alpha$. Strictly speaking, the value of $\tan\theta$, due to the iron alone, is obtained by subtracting the portion of $\tan\theta$, due to the current alone, from the total value of $\tan\theta$, as observed in the main experiment.

124. Determination of the Absolute E.M.F. of a Standard Cell

Apparatus required.—Standard cell (of the Calomel type, or the Clark type). Coil of wire (note 37, p. 229). Copper voltameter. Battery. Adjustable resistance. Mirror galvanometer, and high resistance.

The resistance of a wire can be accurately measured by means of a Wheatstone bridge, and the strength of any current traversing the wire can also be measured accurately by means of the electrolysis of copper sulphate. Hence, since $E = C \times R$, the potential difference between the ends of the wire can be calculated.

This principle may be adapted to the determination of the E.M.F. of a cell in the following manner:—If, while the current is traversing the wire, the + ve and − ve terminals of the cell are connected to the + ve and − ve ends of the wire respectively, the current strength may be adjusted so that the E.M.F. of the cell is just counterbalanced, and no current traverses the cell. This latter condition may be ensured by inserting a mirror galvanometer in the cell circuit, and the arrangement resembles in every detail the comparison of E.M.F. by the potentiometer (p. 161).

The important part of the apparatus is the coil S (conveniently made of No. 28 German-silver wire) (Fig. 104), terminating in thick copper wires which dip into insulated mercury cups. The coil is immersed in a beaker of paraffin oil, which serves to keep the temperature of the coil uniform. The resistance of the coil may conveniently be about five ohms. E is the cell, the E.M.F. of which is to be measured; G is the mirror galvanometer, R_2 is a high resistance (about 10,000 ohms; see note 28, p. 227); R_1 is an adjustable low resistance in the main circuit. The +ve terminal of E is connected to the mercury cup which contains the +ve terminal of the battery B.

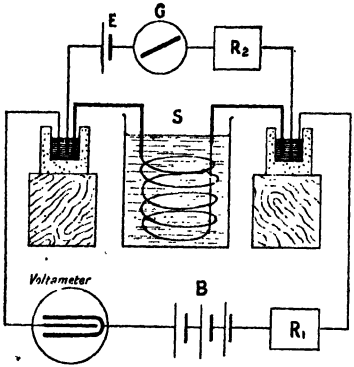


FIG. 104.—Method of determining the absolute E.M.F. of a cell.

(i.) Measure accurately the resistance of the coil S, by means of a Wheatstone bridge (a P.O. box is far preferable). Connect up the apparatus as shown in Fig. 104. Adjust R_1 until there is no deflection in G. Break the circuit. Remove the cathode plate from the voltameter; clean and dry it (as described on p. 180). Weigh the cathode accurately, and replace it in the voltameter. Complete the circuit, and note the time at that instant. Allow the current to continue for about one hour, carefully adjusting R_1, so that no deflection is observable in G. Break the circuit, and note the time at that instant. Weigh the cathode as before, and calculate the current strength (p. 187). Enter your observations thus :—

Standard cell used: Clark type.

Weight in gms. of Cathode.	Duration of Experiment.	Current (= C).	Resistance of Coil (= R).	E = C × R.
Initial . . 13.2568 Final . . 13.7605 Weight deposited = 0.5037	92 minutes	0.276 amp.	5.19 ohms	1.432 volts.

125. Efficiency of an Incandescent Lamp

Apparatus required.—Small incandescent lamp (7 volt, $2\frac{1}{2}$ candle-power). Standard sperm candle (No. 8). Rumford photometer. Tangent galvanometer. Commutator. Potentiometer. Standard cell (of known E.M.F.). Adjustable resistance. Metre scale. Two batteries (each of about six cells of constant E.M.F., and low resistance).

The incandescent lamp, when used as a source of light, is an application of the conversion of electrical energy into heat. The work done in the filament is determined by measuring the current (in amperes) the potential difference (in volts) between the terminals, and the time (in seconds).

$$\text{Total work done} = ECt \text{ (§ 121)}.$$

Hence, the *rate* at which work is done $= \dfrac{ECt}{t} = EC$ units of work per second.

The rate at which work is done is usually measured in **Watts.** *One watt is the rate at which work is done by a current of one ampere working through one volt.* Hence, in an incandescent lamp, the rate at which energy is being expended is determined by measuring the potential difference (in volts) between the terminals, and the current (in amperes) traversing the filament; the product of these two quantities is equal to the rate of expenditure of energy (in watts).

The rate of output of a dynamo is usually expressed in

kilo-watts (1 kilowatt = 1000 watts), and the equivalent *horse-power* may be calculated from the fact that 1 horse-power = 746 watts. The supply of electricity from central stations for purposes of house-lighting, etc., is measured in terms of the *kilowatt-hour*, and the Board of Trade Unit of Electrical Energy is equivalent to one kilowatt of power for one hour.

The **efficiency** *of an incandescent lamp is the ratio of the candle-power developed to the rate of expenditure of energy in the filament (expressed in watts).*

The *candle-power* of a lamp is measured in terms of what is called a *standard candle* (a No. 8 sperm candle, burning 120 grains of wax per hour). The two sources of light are compared by arranging both so that two contiguous shadows of any object are cast on to a white surface. The shadow due to the candle is illuminated by the lamp only,

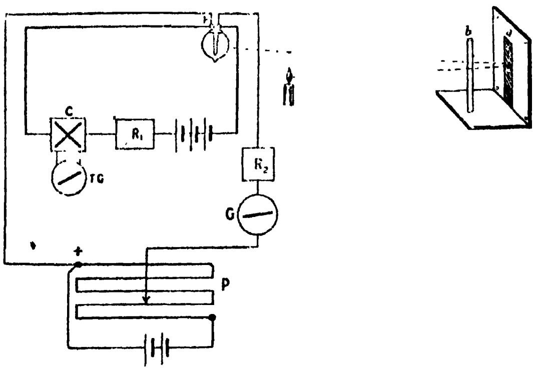


FIG. 105.—Simple method of measuring the candle-power and efficiency of an incandescent lamp.

and that due to the lamp is illuminated by the candle only; the intensity of illumination of these two shadows may be made equal by altering the relative distances of the sources of light from the shadows (see Fig. 105).

The intensity of illumination is directly proportional to the illuminating power of the source of light, and inversely proportional to the square of the distance from the source; or $I = \frac{L}{d^2}$.

Hence, if I_1 and I_2 are the intensities of illumination of the two shadows, illuminated by the candle and the lamp respectively, and if L_1 and L_2 are the illuminating powers of the candle and lamp, then

$$I_1 = \frac{L_1}{d_1^2}, \text{ and } I_2 = \frac{L_2}{d_2^2}$$

But, in the shadow photometer, $I_1 = I_2$

Hence
$$\frac{L_1}{d_1^2} = \frac{L_2}{d_2^2},$$
$$L_2 = L_1 \times \frac{d_2^2}{d_1^2}.$$

The *watts supplied to the lamp* may be determined by measuring the current by means of the low resistance coil of a tangent galvanometer, of which the constant is known; the potential difference between the terminals of the lamp may be measured by comparison with that of a standard cell by means of the potentiometer (P, Fig. 105).

The difference in colour of the shadows is very marked, and will cause much difficulty in determining when the intensity of illumination is the same. It will be found advantageous to view the shadows through a piece of neutral orange-tinted glass, which will render the colour difference less marked.

(i.) Pin a piece of white *blotting* paper on the vertical board (*a*); fix a lead pencil or pen holder (*b*) vertically into the base board, and about six cms. distant from *a*. Fix the incandescent lamp in a wooden clamp, with the filament vertical and broadside towards the board *a*, and at the same height as the candle flame. Also, adjust the positions of the lamp and candle so that their angular distance from the normal to the board is the same. Complete the main circuit through the battery, adjustable resistance, etc., and also connect up the wires leading to the potentiometer, as shown in Fig. 105. Place the lamp at a fixed distance (about fifty cms.) from the board. Adjust R_1 until the filament is heated to redness. Note the deflection in T.G. (also with the current reversed), and the potential difference by means of the potentiometer. Move the lamp nearer to or farther from the board, until the shadows (which should

be contiguous) are equally bright; measure the distance of the lamp's filament from the board (a). Reduce the resistance R_1 slightly, and repeat the observations. Obtain, in this manner, a series of seven or eight readings, with the lamp varying from redness up to brilliant white heat. Enter your results thus :—

Distance (d) of lamp from board (a) = 60 cms.
Constant of T.G. = 0.99.

Potentiometer reading for one standard calomel cell (0.94 volt) = 93.6.

Mean Deflection (a).	C = (K × tan a).	Potentiometer reading.	Watts = (C × E).	Candle Power (L_2).	Efficiency $\left(=\frac{L_2}{C \times E}\right)$.
45°.3	1.0 amp.	559 (= 5.56 volts)	5.56	$\frac{60^2}{99.5^2} = 0.363$	$\frac{0.363}{5.56} = 0.065$
53°	1.314 amp.	707 (= 7.04 volts)	9.25	$\frac{60^2}{46.5^2} = 1.66$	$\frac{1.66}{9.25} = 0.179$
55°.7	1.45 amp.	778 (= 7.75 volts)	11.24	$\frac{60^2}{34.5^2} = 3.02$	$\frac{3.02}{11.24} = 0.270$

Plot out the observations on squared paper, taking the *voltage* as abscissae, and the *efficiency* as ordinates. The curve (Fig. 106) shows not only that the efficiency is greater with higher voltages, but also that the *rate* at which the efficiency increases for an increase of voltage is greater when the lamp is being worked to its fullest capacity. A similar curve may be drawn showing the relationship between the candle-power and the voltage.

An interesting fact regarding the filament is that its resistance is *less* when hot than when cold, and in this respect it differs from all metals. The resistance of the filament may be calculated from the observations already taken, since $R = \frac{E}{C}$; it will be found that the resistance is less when white-

hot than when only red-hot, and in both cases is much less

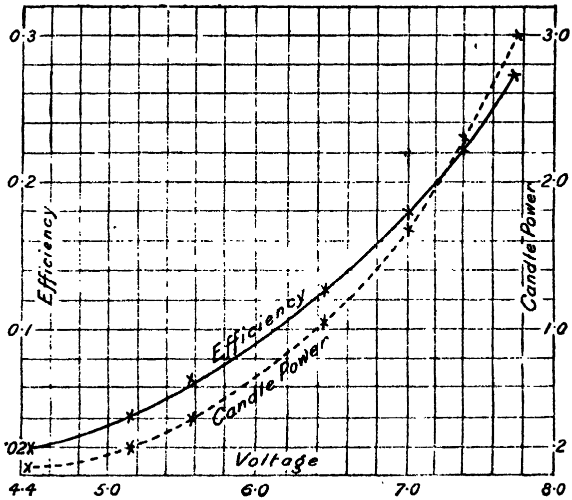


FIG. 106.—Curves showing how the efficiency and candle-power of a lamp depend upon the voltage.

than when the lamp is perfectly cold. This latter measurement might be made with the Wheatstone bridge.

ADDITIONAL EXERCISES

1. A house is supplied with current from public mains at a pressure of 100 volts, and in twenty-four hours takes 4.8 Board of Trade units by meter. Assuming the current to remain constant all the time, state what this current is in amperes, and how many lamps there are lighted in the house, assuming them to be 50-watt lamps. (Evening Exhibitions, L.C.C., 1898.)

2. Sketch and describe the arrangements for finding the *watts per candle-power* of an incandescent lamp. What measurements would you make, and with what instruments? (Evening Exhibitions, L.C.C., 1898.)

3. How would you measure the current supplied to a motor, and the voltage at which it is supplied? If an ammeter and voltmeter are supplied, make a diagram of the necessary connections.

4. How would you proceed to measure the electrical resistance of an incandescent lamp when burning?

5. A battery having an E.M.F. of 25 volts and an internal resistance of 4 ohms is connected by leading wires (resistance = 1 ohm) to an incandescent lamp, at the terminals of which a potential difference of 10 volts is maintained. Compare the electrical power developed in the lamp with that used up in the battery and leading wires.

CHAPTER XXIV

INDUCTION CURRENTS, LENZ'S LAW, ETC.

126. Currents induced by Magnets and by Currents

Apparatus required.—Battery of several cells. Two coils of wire (each coil 10 cms. in diameter, and containing about fifty turns of cotton-covered copper wire) Mirror galvanometer, etc. Strong bar-magnets. Short rod of soft iron.

A magnetic field is always created round a wire conveying a current, and it might be anticipated that the reverse statement would also be true, viz., that the creation of a magnetic field near to a wire, forming a closed circuit, would generate a current in the wire. Faraday, in 1831, found that this latter statement is only partly true, and that a current is only generated when the magnetic field is *altering*. He proved that a current is generated in a closed circuit when a magnet is being *moved* near to the circuit, but that the current ceases so soon as the motion of the magnet ceases. The terms *induced currents* or *induction currents* are used to denote currents which are generated in this manner.

(i.) **Induced Currents generated by a Magnet.**—Set up the mirror galvanometer and scale, and determine by means of a voltaic cell which terminal of the instrument must be + ve in order to give a deflection to the right. Connect the ends of one of the coils of wire to the galvanometer, and place the coil on the bench at a distance from the instrument. Rapidly bring the north-seeking pole of a bar-magnet towards the face of the coil, and observe the simultaneous deflection of the

galvanometer needle. Note whether it is to the *right* or to the *left*. Observe that the current is only momentary, and that it ceases so soon as the magnet is brought to rest. Now suddenly withdraw the magnet and observe the deflection in the *opposite* direction.

Repeat these observations, but move the magnet less rapidly than before. Note that the deflections are now less.

Also, repeat the observations, using the south-seeking pole of the magnet.

Having previously determined the relationship between the direction of current and the direction of deflection, it is easy to trace out the direction of the induced current (Fig. 107) in the

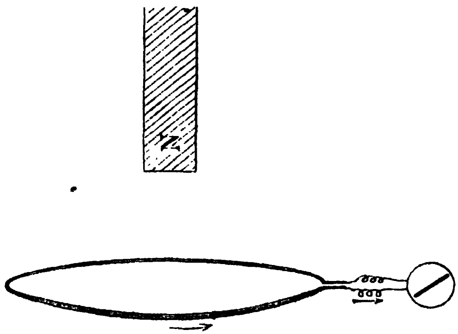


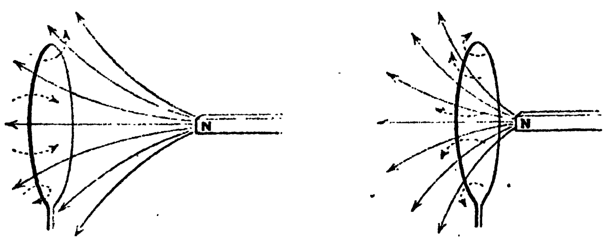
FIG. 107.—North-seeking pole approaching.

coil in each of the above observations. Moreover, since north-seeking or south-seeking polarity is generated at the face of the coil according as the current is in an anti-clockwise or clockwise direction (§ 84), the direction of the induced current may be stated by the magnetic polarity generated in the coil. Enter your observations in the following manner :—

Magnet.	Direction of Deflection (Right or Left).	Polarity of Near End of Coil.
(*a*) North pole approaching		North-seeking
(*b*) North pole receding		South-seeking
(*c*) South pole approaching		South-seeking
(*d*) South pole receding		North-seeking

From these results it is evident that when lines of force are either introduced into, or withdrawn from, the coil an induced current is obtained. It can also be observed that when the magnet is stationary, whatever its position relatively to the coil, no induced current is obtained : in fact, an induced current is only obtained when lines of force are being introduced into, or withdrawn from, the coil. Again, it can be observed in the same experiment that the *strength* of the induced current depends upon the *rate* at which the lines of force are being introduced or withdrawn ; if the magnet is moved slowly, then only a weak induced current is obtained.

It is instructive to examine the results obtained in this



I. Coil approaching. *II. Coil receding*

FIG. 108.

experiment, and to trace out their agreement with the following law of induction :—*When the number of lines of force passing through a circuit is increased or diminished,*

the induced current will be in that direction which tends to keep the number of lines of force constant. Thus Fig. 108, i., represents a north-seeking pole approaching the coil, the number of lines of force passing through the coil being thereby *increased;* the induced current will generate lines of force in the opposite direction (shown by the dotted lines), thus tending to neutralise the increase due to the magnet, and creating north-seeking polarity at the near face of the coil. Fig. 108, ii., represents the magnet receding from the coil.

Make similar diagrams, showing the action of a south-seeking pole when approaching and receding.

The results obtained by means of a magnet in this experiment may also be obtained by means of a coil of wire conveying a steady current of electricity.

(ii.) Induced Currents generated by a Coil conveying a steady Current.– (*a*) Arrange the coil (S, Fig. 109) * and

FIG. 109. -Primary coil approaching secondary coil.

galvanometer as in Expt. 126 (i.) Connect the ends of the other coil (P) to the terminals of a battery, and quickly bring one of its faces into contact with the other coil. Note the direction in which the galvanometer needle is deflected, and from this trace the direction of the induced current in S. Make a simple diagram (as shown in Fig. 109), indicating the direction of the primary and secondary currents, and note down the polarities of the lower face of P and of the upper face of S.

Note down, in the same manner, the effects observed when P is rapidly removed from S, and also when the current in P is reversed. Enter your observations in the following manner :—

* The coil P is called the *primary* coil, and S is called the *secondary* coil.

Primary Coil (P).	Polarity of Lower Face of P.	Polarity of Upper Face of S.
Approaching	South-seeking	South-seeking
Receding	South-seeking	North-seeking
etc.		

(*b*) Similar results to those in the previous experiment can be obtained by keeping the primary and secondary coils in contact, while the current in P is successively made and broken, since, in both cases, the introduction and withdrawal of lines of force through the coil S are effected.

Prove this by making and breaking the circuit of the primary coil, while it remains in contact with S. Also observe the results when the current in P is reversed.

(iii.) **Effect of increasing the Current in the Primary Circuit.**—Place P and S in contact, as in the previous experiment, and carefully note the degree of deflection obtained when the primary circuit is made and broken. Increase the current strength in P by adding one or two more cells to the battery, or by reducing the resistance of the circuit. Again note the deflection obtained, and state whether it is greater than before.

A stronger current in P will, of course, cause *more* lines of force to pass through S, and this apparently creates a stronger induced current in S.

(iv.) **Effect of Soft Iron.**—Hold a short bar of soft iron so that its axis passes through the centres of the coils and is perpendicular to their planes. Repeat the observations described in Expt. 126 (ii.) and note how the induced current is increased.

The soft-iron bar is temporarily magnetised by the current in P, and the total number of lines of force introduced through S is therefore considerably increased, resulting in a stronger induced current.

127. Laws of Current Induction

The law stated in § 126 (i.) referred to the *direction* of the current induced in the secondary circuit. The succeeding experiments have also shown that the strength of the induced current depends not only upon the total number of lines of force introduced through the secondary coil, but also upon the *rate* at which they are introduced.

So far, we have only considered the *current* produced in these induction experiments. No current can be produced without the presence of an E.M.F. giving rise to it, and, moreover, the strength of the current depends upon the resistance of the circuit, whereas the E.M.F. is quite independent of the resistance. Hence, it is more correct to consider the induced E.M.F. rather than the induced current. Induction effects would be obtained if the secondary circuit consisted of only one turn of wire, although they would be so weak that it might be difficult to detect them. If the circuit consisted of two turns of wire in series, then the same E.M.F. would be induced in *each* turn, and the total E.M.F. between the extreme ends of the coil would be twice as great as that generated in a single turn; and if the coil consisted of n turns, then the induced E.M.F. between the ends of the coil would be n times as great. If N lines of force are suddenly threaded through a coil of n turns, then the total number of lines of force threaded through the circuit will be $(N \times n)$, and the induced E.M.F. between the ends of the coil will be proportional to Nn. This result may be expressed in the following law:—*When the number of magnetic lines of force through a secondary circuit is changing, an induced E.M.F. is set up, and the magnitude of the E.M.F. is proportional to the rate at which the number of lines of force changes.*

128. Lenz's Law

This law, stated by Lenz in 1834, affords a convenient method of determining the *direction* of the induced current, and is based upon the following argument:—Energy, in some form or other, is required in order to generate an

electric current. Whence is the energy obtained which gives rise to the induced currents observed in these experiments? It must be due to some external agency, and it originates from the mechanical work done in overcoming mutual electrical forces set up by the relative motion of the two circuits. If this is true, then the mutual electrical forces developed during the approach of the two circuits should tend to hinder their approach, and they should tend to make the circuits approach during the process of separating them.

In each case the induced current is in such a direction as will tend to oppose the relative motion of the two circuits. This relationship holds good in all cases of current induction, and is expressed in the general statement of **Lenz's Law.** *The induced current is in such a direction that its reaction tends to stop the motion to which the induced current is due.*

129. Rotation of a Coil of Wire in a Magnetic Field

Apparatus required. Two strong bar magnets. Coil of wire. Mirror galvanometer.

(i.) Support two bar-magnets horizontally (Fig. 110) with their opposite poles about 15 cms. apart. Connect the ends

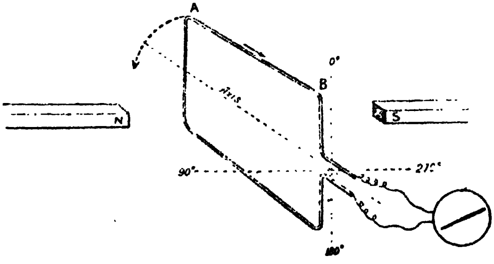


FIG. 110.—A coil of wire rotating in a magnetic field.

of the coil to the terminals of the galvanometer. Hold the coil in a vertical position, mid-way between the two magnets, and with its plane perpendicular to the axes of the magnets. Quickly rotate the coil round a horizontal axis into the position

marked 90° (Fig. 110), and observe the direction of the induced current.

Refer back to the law stated in § 126 (i.); apply it to the present experiment, and deduce whether the induced current should flow from A to B, or from B to A. Does your experiment agree with this deduction?

Continue to rotate the coil, from position 90° to position 180°, and again determine the direction of the induced current. Also determine the directions when the coil is rotated between the positions 180° and 270°, and between 270° and 0°. Make a simple diagram in each case, indicating, by means of an arrow, the direction of the induced current.

It will be found that the induced current is from A to B when the coil is moving between 0° and 180°, and from B to A for the remainder of the complete revolution.

Hence the direction of the induced current is reversed each time the coil passes a vertical position.

130. The Dynamo

The experiment of the previous section explains the principle of the dynamo, all forms of which are more or less elaborate methods of obtaining induced currents by rotating a coil of wire in a strong magnetic field. In such machines the magnetic field is usually created by means of an electromagnet of the horse-shoe type; the coil of wire (termed the *Armature*) is wound round a soft iron core which serves to concentrate the magnetic lines of force *through* the coils.

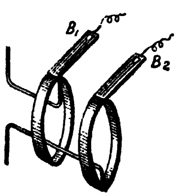


FIG. 111.—Collecting brushes of an alternator.

(i.) **The Alternator.**—Fig. 111 represents a simple method of conveying the induced currents from the armature to the external circuit. Each end of the coil terminates in a metal ring concentric with the axis of the coil. A brush (B), of flexible metal or of carbon, presses against each ring, and the brushes are connected to the terminals of the external circuit. With this arrangement, the direction of the current in the external circuit is reversed

twice in each complete revolution, and gives rise to what is termed an *Alternate Current.*

(ii.) **The Continuous Current Dynamo.**—Fig. 112 represents a simple form of *Commutator*, consisting of a split metal tube fixed to the axis of the coil. One end of the coil is connected to each half of the split tube, and the collecting brushes press upon the outer surface of the tube. By this means the current in the external circuit is always in the same direction, and a *Continuous Current* is obtained.

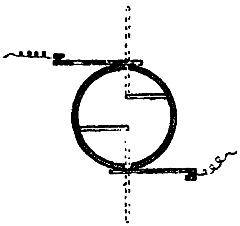


FIG. 112.—Commutator of a continuous current dynamo.

An armature consisting of a single coil of wire is never used in actual practice, since the rate at which lines of force are being cut varies according to its angular position relatively to the lines of force, and the current is therefore very variable. This difficulty is overcome by constructing an armature of several coils, so that when some are yielding a maximum current others are comparatively idle, the combined effect being a steady current.

ADDITIONAL EXERCISES

1. A few turns of fine insulated wire are wrapped round the centre of an iron nail, and the ends of the wire connected to a sensitive galvanometer. State and explain the effect on the galvanometer (1) when the nail is put across the poles of a horse-shoe magnet, slowly or quickly, (2) when it is slowly or quickly removed. (1890.)

2. An iron hoop is held in the magnetic meridian and is allowed to fall over towards the east. Explain why an electric current traverses the hoop, and state whether the current would flow north or south in the part of the hoop which touches the ground if the experiment were performed in England. (1894.)

3. A flat coil of wire, the ends of which are connected to a

sensitive galvanometer, is (1) moved up towards the north end of a long bar-magnet, (2) threaded on the bar, (3) moved along it to the south end, (4) removed to a distance. What indications does the galvanometer give during these operations? (1897.)

4. A vertical hoop of wire, at right angles to the magnetic meridian, is quickly, but with uniform speed, turned through 180° about a vertical axis, its originally eastern half moving northward at first. State the direction in which the induced current passes round the wire, and determine the position of the hoop in which the induced E.M.F. is the greatest. (1898.)

5. Describe the construction and explain the action of a magneto-electric machine for the conversion of mechanical work into current energy. (1899.)

6. Two coils of wire are placed in contact with each other, and with their axes in line. The ends of one coil are fastened to a battery, those of the other to a mirror galvanometer. A soft-iron bar is inserted through the coils, and a momentary current is observed, and a reverse current is obtained when the bar is withdrawn. Explain these observations.

CHAPTER XXV

Construction of Apparatus

1. **Methods of Suspending Lodestone or Magnet.**—A lodestone, or a heavy magnet, is best suspended by means of silk *cord* (not sewing silk), which can be purchased from a draper; or, a bundle of loose *unspun* silk may be used. Needles may be suspended either by single fibres of unspun silk or by a long piece of copper tinsel; in either case hooks of thin copper wire should be fastened to the lower end of the fibre or tinsel. (Tinsel may be obtained from Mr. G. Kenning, 1 Little Britain, E.C.). Since students often find difficulty in handling these delicate supports, an alternative method is shown in Fig. 4; in this, a short test-tube (2 inches long) rests inverted on the point of a darning-needle fixed vertically in a wide cork, and a small lump of soft wax enables the needle to be attached to the closed end of the test-tube. In order to ensure stable equilibrium, a strip of sheet lead is cut to a length necessary to form a collar which can be slipped over the outside of the test-tube and resting on its expanded rim.

2. **Soft Wax.**—The soft red wax which is used in post-mortem cases is very convenient for the purpose. It can be obtained from most dealers in physical apparatus.

3. **Galvanised Iron Strips.**—Galvanised iron is made by dipping sheets of soft iron into molten tin, and is used in making biscuit-tins and tobacco-tins. These may be cut up into fragments of suitable size for these experiments.

4. **The Magnetometer.**—Cut the base board, in ½-inch deal, to the dimensions shown in Fig. 9, and strengthen it by screwing to its under surface the wooden parts shown in the end and side views. Cut the first 6 cms. from each of two centimetre scales, each 50 cms. long, and fix these in position so as to measure exact distances from the centre of the graduated circle. Also, fix against the divided edge of each scale a thin strip of wood, projecting slightly above the level of the scale, to serve as a guide in placing the bar-magnets in position. Use *brass* screws throughout. Fix the graduated circle (10 cms. diameter) to a circle of thin wood, of nearly the same thickness as that of the wooden scales, and fix this symmetrically to the base board.

Bore a fine hole in the centre of the circle, and fix in the hole the end of a sewing-needle, point upwards. Support the apparatus on three feet (made by soldering a brass screw through the centre of a brass disc).

The needle (Fig. 113) may be prepared in the following manner :—Close the end of a piece of narrow glass tubing and blow the end to a

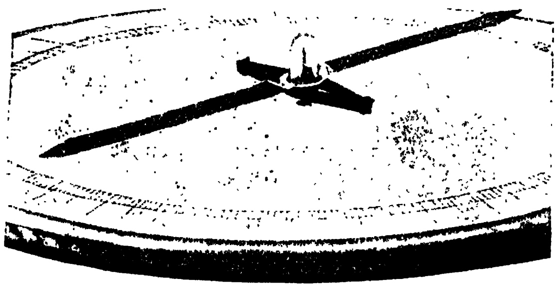


FIG. 113.—The needle of a magnetometer.

hemispherical form. Cut off about 1 cm. length of this closed end. Magnetise two pieces of watch-spring (2 cms. long) and bind the ends together by thin copper wire, and with similar poles in contact. Pass the glass tube between the centres of the magnets and rigidly fix them with a spot of sealing-wax. Cut the pointer from thin aluminium foil, and bend the free ends into a vertical plane.

A glass crystallising dish (11.5 cms. diameter, 6.5 cms. deep) serves as a suitable cover for the swinging magnet.

5. **Method of preparing Paraffined Paper.**—Melt some white paraffin-wax in a shallow tin, sufficiently large to take half a sheet of foolscap paper ; heat the wax until it is *nearly* boiling. Pass a sheet of *thin* white paper once through the wax, and hold it vertically until the wax has solidified.

6. **Simple Dip Needle.**—Select an unmagnetised knitting-needle about 12 cms. long. Construct an axle for the needle in the following manner :—Hold two short pieces of copper wire on opposite sides of and at right angles to the length of the needle. Twist the ends of the wires together on each side so as to grip the needle tightly, and carefully straighten the twists. Make the wire surfaces as smooth as possible by heating in a gas flame and applying sealing-wax, shaking off the excess of wax while still fluid (Fig. 17, ii.). Apply a spot of sealing-wax so as to rigidly connect the axle to the needle. Make a support for the needle by cutting two rectangular pieces of sheet brass or copper (7 cms. × 1 cm.), rigidly connect them together at the base

with their short edges horizontal and 1 cm. apart, and fix them to a suitable base board (or a support may be made with two pieces of glass rod fixed horizontally and 1 cm. apart). Attach a circular scale of 90° to one of the supports (Fig. 17, i.). See whether the needle is truly balanced by supporting it by its axle on the knife-edges; if necessary, adjust the position of the axle by slightly warming the sealing-wax joint and moving the axle along the needle. Carefully magnetise the needle.

7. **A Simple Magnetoscope** (Fig. 26).—Select a glass tube, about 20 cms. long and 2 cms. internal diameter. Bore a hole through a flat cork, the hole being sufficiently wide to serve as a stand in which the tube may be fixed. Fit a cork into the upper end of the tube, and insert a short length of stout copper or brass wire, bent at right angles through the cork. Break off a short length (about 1.5 cms. long) of a rat-tail file, and magnetise it strongly. Tightly twist a short length of copper wire round this magnet, having a free end of wire about 2 cms. long. Now suspend the magnet by means of a silk fibre attached to the wire at the top of the tube. Attach four silvered microscope cover-glasses to the copper wire in the positions shown, so that some one of the mirrors will be in a convenient position from which to reflect a beam of light, and in this manner to determine with fair accuracy the time occupied by any observed number of swings. Fig. 26, ii., represents a simple form of "sighter," which can be made with glass rods, corks, and cardboard; this ensures that the eye of the observer shall occupy the same position during the period of an experiment. A Price's night-light standing in a shallow glass vessel is a convenient source of light.

Stop-watch.—Stop-watches suitable for experimental work may be purchased cheaply (7 to 8 shillings each).

8. **Box for Vibration Experiments.**—(i.) Make a wooden box (18 cms. × 11 × 8½), leaving the ends open. Select a piece of glass tube (28 cms. long, and 2 cms. diameter), and bore a circular hole in the centre of the top of the box, of sufficient diameter to enable the glass tube to be fixed in firmly with cement. Fit a cork into the top of the tube; pass a short piece of stiff brass wire through the cork, and bend the upper end of the wire at right angles to enable the wire to be adjusted. Solder to the lower end of the wire a length of copper tinsel, terminating in a wire hook from which the magnet may be suspended. Make a light stirrup of thin copper foil, and fix to its under surface a narrow strip of aluminium foil (16 cms. long), the extreme ends of which are bent at right angles. Cut two pieces of glass of sufficient size to close the ends of the box (¼-plate negative glasses are convenient); fix the glass ends in position by means of elastic bands or by soft wax. Attach a narrow strip of paper down the middle of each glass plate (Fig. 32).

If the magnet is sufficiently light it should be suspended by means of a silk fibre, and the stirrup should be as light as possible. (For

alternative types of stirrup, see Fig. 4.) Copper tinsel will be found necessary in the case of heavy magnets.

(ii.) A simpler apparatus (Fig. 33) for carrying out the same experiment may be arranged by means of a glass crystallising dish and sheet of paper. Fix two narrow (1 mm. wide) strips of white paper vertically to the sides of the dish and at opposite ends of a diameter. Also fix a similar piece of thin paper to the vertical end-face of the magnet. Suspend the magnet inside the dish. Cut a circular hole (2 cms. diameter) in a piece of paper, and slit the paper in any one direction from the hole to the edge so as to enable the paper to be placed over the dish without disturbing the magnet. Move the dish round until the diameter joining the strips of paper is in the magnetic meridian.

9. **Mirror Magnetometer.**—(The details of this apparatus are mainly taken from Stewart and Gee's *Practical Physics*, vol. ii.) The dimensions of the wooden stand are shown in Fig. 114. The base board is supported on three levelling screws (made by soldering a brass

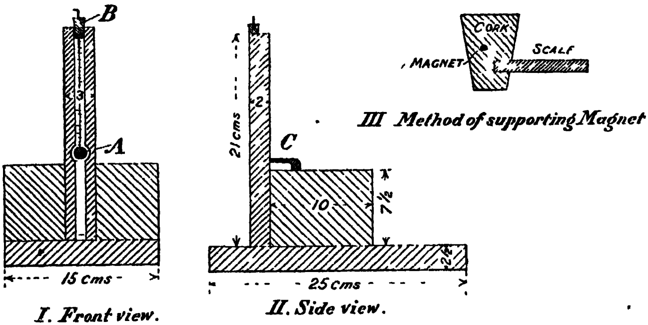


FIG. 114.

screw through the centre of a brass disc, about the size of a penny). A shallow groove is cut along the face of the upright, and a circular hole is cut at A, sufficiently large to allow the mirror to swing freely. The mirror, to the back of which a short piece of magnetised watch-spring is attached, is supported by silk fibre which hangs from a short brass wire supported through the square cork B, which fits tightly into the upper end of the groove. C is a wooden button which serves to hold a wooden metre scale in position at the same level as the needle. The mirror is protected from air currents by a strip of glass fixed against the face of the upright by means of soft wax.

Preparation of the Magnet.—Bind together, by means of iron wire, several pieces of knitting-needle, each about 7 cms. long; heat

them to redness in a blow-pipe flame, and allow them to cool slowly. File the ends true, and straighten the wires if necessary. Again bind them together, heat to bright redness, and plunge them vertically into a vessel of cold water. Clean the surfaces, if necessary, with emery paper, and magnetise them strongly by means of a helix and battery. One of these magnets will suffice for the purposes of the experiment.

The deflecting magnet may be supported on the wooden scale by means of a cork (Fig. 114, iii.), in the side of which a rectangular groove is cut. The magnet should be horizontal and with its axis in line with the centre of the deflected needle.

The lens may be supported conveniently in a slit cut in a cork which is supported on the upper end of a glass rod; the rod passes tightly through the cork of a shallow bottle, thus allowing the height of the lens to be adjusted.

A suitable arrangement for the lamp and scale is shown in Fig. 78, and is described on p. 226.

10. **Glass rods.**—These should be made from *lead* glass (not *soda* glass).

11. **Drying Oven.**—A portable drying oven may be constructed in the following manner. Fill a shallow baking-tin (about 40 cms. × 20 cms.) with sand, and cover it with a sheet of thin iron (about 40 cms. × 35 cms.) bent into the form of a semi-circle, so as to form a hood over the sand bath. The bath is supported on tripods, and heated by Bunsen burners placed underneath. Glass rods may be placed in the sand, and paper, flannel, silk, etc., may be spread over the hood.

12. **Pith-ball Electroscope.**—Fix a rod of vulcanite to a flat cork (or other suitable base) so that the rod stands in a vertical position. Bend the end of a piece of stout copper wire (5 cms. long) into a hook, and fasten it to the top of, and at right angles to, the rod. From the hook suspend a gilt pith-ball by means of very thin copper wire (or cotton thread). It is important to avoid skarp metal points, a difficulty which is readily overcome by fusing the ends of the wires in a blowpipe flame or by covering the ends with a spot of sealing-wax or soft wax. A pith-ball is satisfactorily "gilded" by moistening the surface with weak gum and, when nearly dry, rolling it in gold leaf (Dutch-metal leaf or aluminium leaf are satisfactory substitutes for gold leaf.)

13. **Two Appliances for Determining the Direction of Electrostatic Lines of Force.**—(i.) Pierce a small circular hole through a piece of thin paper (3 cms. × 0.5 cm.). Pass a piece of drawn-out glass tubing through the hole, and allow the paper to be quite free to move. Using the glass tube as a handle, bring the paper

near to an electrified body. The paper will point in the direction in which the electric forces are acting (Fig. 39).

(ii.) Fix two long pieces of glass rod in a cork, and bend the rods so that they form a large V. Bore a hole in a small cork, so that it will fit tightly on the end of one of the rods. Attach one end of a silk fibre to this cork, and the other end to the free end of the other glass rod. The fibre may be tightened by rotating the small cork. To the centre of the fibre attach another short fibre (about 2 cms. long), which carries the *pointer*. The pointer consists of a piece of fine copper wire (5 cms. long), on the ends of which are threaded two small gilt pith-balls. Adjust the pith-balls so that the pointer hangs freely in a horizontal position (Fig. 38).

14. **The Gold-leaf Electroscope.**—A simple form of this instrument may be made from a cigar-box in the following manner:—Remove the top and bottom of the box and cut away the lower portions so as to have sufficient open space for glass plates (photographic ½-plate is a convenient size) to slide in shallow grooves cut in the woodwork. Changes in the divergence of the leaves are observed readily if the glass surface is divided into squares by means of ink lines, which are ruled readily in Indian ink on the dry gelatine film of a photographic plate from which the silver salts have been removed by solution in sodium hyposulphite; an alternative method is to support a portion of a circular paper scale on a vertical rod of sealing-wax and immediately behind the leaves. Cover the internal wood surface of the box with tin-foil. The insulation is obtained most satisfactorily by means of a plug of sulphur, supported in a circular hole bored in the end of the box. The plug is prepared by pouring liquid sulphur, which has been melted *slowly*, into a paper mould made by wrapping paper round a cork; the lower end of the mould is closed by a disc of cork pierced by a straight piece of thick copper wire which will subsequently carry the gold leaves; the paper should be cut away from the plug while it is still hot. Taper off the lower end of the wire to a flat edge, and solder to it a rectangular strip of sheet copper. Support a metal disc on the upper end of the wire by means of a short length of metal tube, or a closely wound spiral of wire, soldered to the centre of the disc. Cut two leaves, each about 5 cms. × 1 cm., and attach them to the lower end of the wire, which has been moistened previously with a minimum quantity of weak gum and allowed to become nearly dry. In order to cut Dutch-metal (or gold) leaf, spread a sheet of thin well-glazed paper on a sheet of glass, and lay the metal leaf on the paper. Cover the leaf, except a strip of the width required, with a second sheet of paper; and cut off the strip by means of a sharp razor, using the edge of the paper as a guide.

15. **The Proof Plane.**—The proof plane is a simple appliance which will be frequently required for experiments on induction; it

consists of a disc of thin copper or brass (about 2 cms. diameter) fixed to the end of an insulating handle. A half-penny may be used as a metal disc.

16. **Insulating Stands.**—A simple form of insulating stand is frequently required in electrostatic experiments. Flat slabs of white paraffin-wax serve the purpose admirably. The wax may be cast by melting it in a baking-tin of the required size, and allowing it to cool; when cold the tin is placed in hot water for a few moments, till the outer layer of wax is melted, and then inverted, so as to remove the slab of wax. The wax should be originally melted by standing the tin in a vessel of water heated from below, since the wax loses its insulating power considerably if heated much above the temperature of boiling water.

If a taller insulating stand is required, a suitable form may be made in the following manner:—Fix a stout glass tube (*lead* glass should be used) vertically into a wooden base. Bore a hole in a wide cork so as to fit tightly on the upper end of the glass tube. Fix a slab of wax horizontally on the top of the cork. The insulation is improved by varnishing the glass tube (Fig. 49).

17. **An Electrophorus.**—A simple form of electrophorus may be made by filling the inverted lid of a coffee-tin (8-10 cms. diameter) with melted sealing-wax. Cut a circular disc of brass or copper of slightly less diameter than the tin lid, and fasten the disc at right angles to the end of a rod of vulcanite, which serves as an insulating handle; the portion of the brass surface to which the handle is attached should be previously scratched or roughened, to enable the vulcanite to cling more firmly.

18. **Electrostatic Condenser.**—(i.) Fig. 53 represents a simple form of condenser, consisting of two sheet-zinc plates A and B, bent at right angles, and of which the vertical portions are about 15 cms. square. C is simply a vertical plate of slightly larger area than A or B. All the plates are fastened to horizontal rods of sealing-wax. For some experiments a millimetre scale will be required.

(ii.) Fig. 54 represents a more elaborate form of condenser. A and B are two plates of stout sheet brass (15 cms. diameter), the surfaces of which have been truly planed in a lathe. At the back of each plate is a central brass socket, into which the end of a vulcanite rod is fixed, and also a binding screw fixed near to the edge. The vulcanite rods are half-inch diameter, and each is supported from a brass socket which is screwed to rectangular wooden blocks. The base board consists of a plane wooden support (30 cms. × 10 cms.) to the edge of which a millimetre scale is screwed. Plate C is a convenient adjunct for examining the field of force betweeen the plates of the condenser. Slabs of wax, etc., may be supported between the plates on a block of wood in which a shallow rectangular groove is cut.

19. **Flask to show Heating Effect** (Fig. 59).—Fit a cork to a 16-oz. flask. Bore a hole through the axis of the cork, wide enough to carry a piece of narrow glass tubing bent at right angles. Insert two copper wires through the cork, and as far from each other as possible; allow the lower ends of the wires to terminate well inside the body of the flask. Join the lower ends of the copper wires by means of a narrow strip of thin tinfoil. Make sure that the cork is thoroughly air-tight.

20. **Boiling-tube to show Chemical Effect** (Fig. 60).—Cut two pieces of thin platinum wire (each about 4 cms. long) and solder to the ends of pieces of copper wire. Cut two pieces of narrow glass tubing (about 15 cms. long), and draw out one end of each piece to a capillary tube. Fuse the platinum wires into the capillary ends of the tubes, and cut off the ends of the wires as close to the glass as possible. Bend the ends of the glass tubes to a right angle. It is now necessary to grind the ends of the wires on glass with wet emery powder, so that only cross-sections of the wires are exposed. Mount the glass tubes in a cork, as shown in Fig. 60, and partly fill the boiling tube with water acidulated with sulphuric acid.

21. **Battery of Simple Cells.**—A suitable form of battery may be constructed in the following manner:—Bore a row of twelve shallow holes ($\frac{1}{2}$ inch in diameter, and 1 inch apart) in a strip of wood (14 inches $\times$ 2 $\times$ 2). Place in each hole a small test-tube or sample-tube (2 inches by $\frac{1}{2}$ inch). Cut twelve strips of sheet copper $1\frac{1}{2}$ inch $\times$ by $\frac{1}{4}$ inch) and an equal number of sheet-zinc strips of the same size. Solder the ends of the copper strips to the zinc strips so as to make twelve separate zinc-copper strips. Bend each compound strip so that the copper dips into one tube and the zinc into the next tube. Nearly fill each tube with *very* dilute acid. To ensure perfect insulation it is advisable to paint the wooden stand with melted paraffin-wax. The arrangement now forms a series of twelve cells, and the potential difference between the extreme ends is twelve times as great as the difference between the plates of one cell. It is an advantage to have even a greater number of the cells connected together, by making another complete set of twelve cells similar to the set described above, and connecting the two sets so as to form a series of twenty-four cells (Fig. 65).

22. **The Condensing Electroscope** (Fig. 64).—The plates should be made of stout brass (about 20 cms. diameter), the surfaces of which have been turned in a lathe. The lower plate is supported on a vertical rod of unpolished vulcanite, which is mounted on a suitable base. The upper plate is also supplied with a vulcanite handle. Two binding screws are fixed to the outer surface of each plate, and at opposite ends of a diameter. Lacquer (or varnish) both plates, *but not the binding screws.*

23. **The Commutator** (Fig. 66) consists of a square block of wood, with a circular hole bored in each corner to serve as mercury cups. The cups are connected diagonally by thick copper wires. The swinging arm consists of two pieces of bent copper wire, which are insulated from each other by means of a short piece of glass tubing; the arm carries two pieces of thick wire bent into an arc, which can be made to dip into either pair of mercury cups by swinging the arm over in the required direction; also, two thick copper wires which dip into two of the cups on one side of the block serve as terminals to which the ends of the outer circuit are connected.

24. **Solenoids** (Fig. 69).—Wind a spiral of fairly thick cotton-covered copper wire round a cardboard tube (5 cms. diameter and 20 cms. long). Fix each end of the spiral to the tube by tying the wire with thread, which passes through small holes pierced in the cardboard. Bend the free ends of the wire along the outside of the tube and towards the centre, and again bend them at right angles so as to dip down into concentric mercury cups placed underneath. The mercury cups shown in the figure are made by glueing together two pill-boxes, of different diameter, one inside the other. Connect each mercury cup to an external binding screw by means of copper wire. One of the ends of the spiral is bent, so that it is in a vertical line with the suspension and dips into the inner mercury cup; the other end is bent so as to dip into the outer cup. The mode of suspending the spiral is clearly seen in the diagram (Fig. 69).

Make a second spiral, which can be held in the hand in order to test its action on the suspended spiral when a current is traversing both spirals.

25. **A Simple Galvanoscope.**—Procure a small wooden box, 8 cms. long, 6 cms. wide, and 3 cms. deep (Fig. 70). Remove the ends from the box, cut a transverse slit (4 cms. × 0.5 cms.) across the middle of the lid, and bore a circular hole (1 cm. diameter) in the centre of the bottom of the box; if a suitable box is not available, four pieces of wood may be cut to the required size and glued together. Wind about eight layers of No. 32 cotton-covered copper wire over each end of the box, and afterwards dip the box into melted paraffin-wax. Fix a thin piece of wood to each end face of the box, to serve as supports for the box, and also for the screw terminals of the coil. Join these terminals to the external terminals on the base board by means of copper wires which pass through holes to the under surface of the base board. (These copper wires also serve to rigidly hold the instrument on the base board.) Mount a graduated paper circle (about 6 cms. diameter) on a piece of millboard, and cut away a narrow slit (4 cms. long) along the diameter connecting the 90° readings of the circular scale.

Fig. 115 shows how the needle and pointer may be constructed from

two pieces of magnetised clock-spring which are fixed, by means of sealing-wax, to the lower end of a piece of drawn out glass tubing, to the top of which the glass pointer is attached exactly at right angles to the magnetic axis of the needles. Support this arrangement on a vertical steel needle which is fixed (point upwards) in a cork inserted in the circular hole in the base of the box. Support the base board on three brass screws screwed into its under surface. When the instrument is completed adjust the verticality of the needle by moving the position of the cork. Protect the needle from air currents by covering the coils with an inverted glass crystallising dish, resting on the base board.

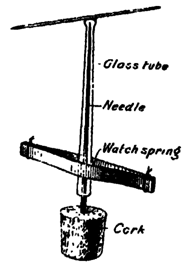


FIG. 115.—Needle and pointer of a galvanoscope.

26. **The Tangent Galvanometer.**—(i.) The apparatus really consists of the magnetometer (described on p. 216), supported horizontally on two vertical uprights in which grooves are cut so as to enable the magnetometer to be supported firmly in a series of different positions in the same horizontal plane. Turn a circular ring of wood *B* (25 cms. diameter), and cut a shallow rectangular groove round its outer edge. Carefully measure the circumference of the groove. Wind four separate layers of double cotton-covered copper wire (No. 22, S.W.G.) round the groove, carefully counting the number of turns of wire in each layer; it is an advantage to have one coil consisting of only four or five turns of thicker wire; allow the ends of each layer to enter and leave the groove through narrow holes bored through the edge of the ring, in each case the holes being exactly opposite one another, so that each layer contains a known number of *complete* turns of wire. Fix two vertical pieces of wood across the middle of the base board, by means of which the coil of wire may be clamped in position, and accurately adjusted so that the centre of the coils coincides with the horizontal line in which the magnetometer needle is situated. Fasten the ends of the coils to a series of binding screws fixed to the base board, so that the ends of coil No. 1 are connected to terminals 1 and 2, the ends of coil No. 2 to terminals 2 and 3, and so on. Support the base board on three levelling screws.

(ii.) A simpler form of tangent galvanometer, in which the circular scale and needle are permanently fixed at the centre of the coil, will suffice for most experiments.

27. **Mirror Galvanometer*** (Fig. 77).—Cut two pieces of wood (10 cms. square, and 1.5 cms. thick), and bore a circular hole ($2\frac{1}{2}$ cms.

* The details of this instrument are mainly derived from Professor J. A. Fleming's *Magnets and Electric Currents* (E. and F. W. Spon).

diameter) through the centre of each. Coat with paste one side of a piece of foolscap paper (30 cms. × 10 cms.), and lay the paper paste-side downwards on a clean board, and roll it up tightly on a wooden or metal cylinder (of such diameter that the paper tube will fit tightly into the circular holes cut in the pieces of wood). Slide the paper tube off the cylinder, allow it to dry, and then trim the ends so as to obtain a tube 7 cms. long. Fix the pieces of wood to the paper tube and wind on to the tube about ten layers of No. 34 cotton-covered copper wire. Solder the bare ends of the coil to two small pieces of sheet copper, through the centre of each of which a terminal is screwed into the upper edge of one of the wooden faces.

Procure a plane galvanometer mirror * (half-inch diameter). Cut a disc of aluminium foil (half-inch diameter) leaving three short tongues projecting from the edge (Fig. 116, i.), and fix two or three short pieces of magnetised watch-spring to the back of the foil. Place the mirror, glass-side outside, against the foil, and bend the metal tongues round so as to hold the mirror in position. Attach a short piece of single silk fibre by means of shellac to the metal tongue vertically above the magnets. Fig. 116, ii., shows how the mirror may be suspended from the end of a stiff brass wire which is supported by a cork fitting into the back of the paper tube.

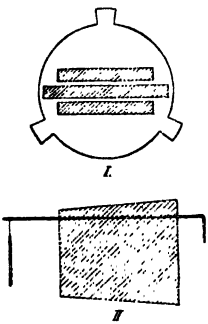


FIG. 116.—Method of supporting the magnets and mirror.

It is frequently necessary to use a controlling magnetic field. This may be provided by means of a bar-magnet placed on the bench near to the instrument, or by means of the arrangement shown in Fig. 77, in which a piece of strongly magnetised knitting-needle is supported horizontally in a cork which slides up or down a glass rod fixed to the back of the galvanometer.

Fig. 78 represents a simple arrangement for the lamp and scale. Select a deal packing-box (A), sufficiently large for the lamp to be placed inside, and remove the ends and top. Cut a sheet of stout millboard (B) to the same length and width as the box, cut a narrow slit (C) down the middle of the millboard, and stretch a thin copper wire along the middle of the slit; tack the millboard to the front of

* A mirror may be prepared by silvering a microscope cover-glass, the surface of which is uniformly plane. The trueness of the surface may be ensured by laying the coverslip on a dark surface and observing whether the reflected image of any objects with straight edges is free from distortion; it will be found that the majority of the coverslips have not a sufficiently true surface for the purpose required.

the box. Attach a paper centimetre scale to a strip of wood (D), to the upper edge of which two loops of wire are attached. Support the lens (L) in a slit in a cork, fixed to the top of a glass rod which is supported through the cork of a wide-mouthed bottle.

28. **A Simple Form of High Resistance.**—This may be constructed by ruling lead-pencil lines on a sheet of glass with *matt* surface (Fig. 79). The wires are connected to the pencil lines by means of battery terminals, with which good contact may be ensured by interposing a few thicknesses of tinfoil between the glass and the screw terminal. If the lines are drawn in zigzag form variations of the resistance are easily obtained by moving one of the screw terminals.

29. **Adjustable Resistances.**—There are two forms which are convenient and not costly. One consists of layers of carbonised cloth through which the current is made to pass; the resistance is varied by means of a screw which compresses the layers more or less closely together. Another convenient form consists of several slabs of hard carbon placed face to face, instead of the layers of carbonised cloth.

It may be convenient for some purposes to construct a liquid resistance as shown in Fig. 92; zinc plates and a solution of zinc sulphate are suitable for the purpose.

30. **Apparatus represented in Fig.** 91.—Fit a cork into a glass boiling tube. Boil the cork in paraffin-wax. Wind about two metres of No. 28 iron wire into a long narrow spiral, and solder the ends to short pieces of thick copper wire. Bore holes through the cork to carry the thermometer, the terminals of the spiral, and a stirrer (made of thick copper wire). Fill the tube with paraffin oil.

31. **Apparatus represented in Fig.** 92.—Fit a cork into each end of a glass tube (40 cms. × 2 cms.). Boil the corks in paraffin-wax. Cut two circular discs of sheet copper, sufficiently large to pass readily into the tube, and solder a long piece of thick copper wire to the centre of each disc. Through the centre of the corks pierce a hole sufficiently large for the copper wires to pass through.

32. **Standard Calomel Cell.**—This cell may be constructed in the following manner:—Procure a glass tube (6 cms. long, $2\frac{1}{2}$ cms. diameter) provided with a cork which has been boiled in paraffin-wax. Through the cork bore two holes, one supporting a rod of pure zinc, the other supporting a narrow glass tube sufficiently long to reach to the bottom of the wide tube. Fuse a platinum wire into the lower end of the narrow tube, and connect the inner end of the platinum to a copper wire, which will serve as one of the terminals of the cell. Solder a copper wire to the upper end of the zinc rod. Pour a little pure mercury into the wide tube, and insert the platinum terminal so that it is completely covered by the mercury. Put pure mercurous chloride over the mercury to a depth of about 2 cms. Nearly fill the

tube with a saturated solution of pure zinc chloride, and insert the cork and zinc rod; adjust the latter so that it dips into the zinc chloride, but does not touch the layer of mercurous chloride. Fix the cell on a block of wood to serve as a support, and screw terminal binding screws into the top of the block.

It is convenient to have three or four of these cells mounted on a long block of wood, and connected in series.

33. **Joule's Law** (Fig. 96).—Make a cylindrical vessel (10 cms. high, 5 cms. diameter) of thin sheet copper. Fit a cork into the top of the vessel, and previously boil the cork in paraffin-wax. Bore holes in the cork, one in the centre for the thermometer, and two holes at opposite ends of a diameter for the leads of stout copper wire; all of these should be tightly fitting. Also bore a hole through which the handle of the stirrer may readily pass. The handle of the stirrer should be protected by a short piece of glass tubing in order to prevent the passage of heat from the hand. The coil may consist of bare German-silver wire (No. 28), of sufficient length to have a resistance of about 20 ohms. Any possibility of the current short-circuiting through the water may be prevented by coating the wire with a very thin layer of hardened shellac: this may be done by dipping the coil into a weak solution of shellac in methylated spirit contained in a beaker, and afterwards drying the coil in an air oven at 130° C.; the coil should be again dipped and dried.

In comparative experiments it may be found more convenient to use turpentine, instead of water, in the calorimeter. It has less heat capacity than water (Sp. Ht. of turpentine = 0.462), and therefore less time is required in order to obtain a measurable rise in temperature. The use of turpentine also allows the wire (single silk-covered) to be wrapped into a coil without any liability of short-circuiting, thus allowing more wire to be used than if an open spiral only were permissible. The thermometer should be graduated to 0°.5 (or preferably to 0°.2).

34. **Copper Voltameter** (Fig. 99).—The support for the copper plates consists of two rods of vulcanite joined together by three parallel wires of stout copper; this support rests on the edge of a large beaker. The two outer copper plates (the anodes) may conveniently be about 7 cms. long and 5 cms. wide; the middle plate (the kathode) should be slightly smaller (say 6 cms. × 4.5 cms.). Use a 15 per cent solution of copper sulphate, to each litre of which 5 c.c. of strong sulphuric acid have been added.

35. **Water Voltameter** (Fig. 101).—Procure a wide-mouth bottle (about 8 ozs. capacity), fitted with a rubber stopper. Pass two stout copper wires through the stopper at points about 2 cms. apart. Solder to the lower end of each copper wire a short length of platinum wire, and to each of these weld a piece of platinum foil (about 3 cms. × 1 cm.). The welding is conveniently done by laying the foil and wire

in contact on a non-conducting surface (*e.g.* a brick); heat the foil and wire to bright redness with a blowpipe flame, and hammer them while red-hot at the required point of junction. Fix the glass-leading tube through a hole in the centre of the stopper. Since a hot platinum wire may ignite the explosive mixture of gases which will accumulate in the bottle, it is preferable to protect the copper and platinum wires inside a glass tube, the lower end of which is fused round the platinum wire at its lowest point.

The acid solution may be prepared by adding one vol. of strong sulphuric acid to four vols. of water.

36. **Solenoids.**—A convenient form of solenoid may be made by winding a close spiral of No. 32 cotton-covered copper wire on a glass tube (25 cms. long, and 0.4 cm. external diameter). Another solenoid of the same dimensions should be made with No. 22 copper wire. Each end of the spiral may be held in position by passing the wire under a short length of narrow rubber tubing which is slipped over the end of the glass tube; the free ends should be bent back along the spiral, and terminating at the middle of its length.

37. **Coil of Wire** (for absolute E.M.F. of a cell).—No. 28 German-silver wire (silk-covered) is suitable, and it should be of sufficient length to give a resistance of about 5 ohms. Wind the wire on a wooden reel, and solder the ends to thick copper wires bent twice at right angles. Immerse the reel in a beaker of paraffin oil. Each of the thick wires should dip into separate mercury cups, which may be made by partly boring a wide hole in a large cork, which has been boiled in paraffin-wax.

NATURAL TANGENTS.

(In most cases it is sufficiently accurate to use the values to four figures.)

Angle.	.0 =.0′.	.1 =6′.	.2 =12′.	.3 =18′.	.4 =24′.	.5 =30′.	.6 =36′.	.7 =42′.	.8 =48′.	.9 =54′.
0°	.00000	.00174	.00349	.00524	.00698	.00873	.01047	.01222	.01396	.01571
1	.01745	.01920	.02095	.02269	.02444	.02619	.02793	.02968	.03143	.03317
2	.03492	.03667	.03842	.04016	.04191	.04366	.04541	.04716	.04891	.05066
3	.05241	.05416	.05591	.05766	.05941	.06116	.06291	.06467	.06642	.06817
4	.06993	.07168	.07343	.07519	.07695	.07870	.08046	.08221	.08397	.08573
5	.08749	.08925	.09101	.09277	.09453	.09629	.09805	.09981	.10158	.10334
6	.10510	.10687	.10863	.11040	.11217	.11394	.11570	.11747	.11924	.12101
7	.12278	.12456	.12633	.12810	.12988	.13165	.13343	.13520	.13698	.13876
8	.14054	.14232	.14410	.14588	.14767	.14945	.15124	.15302	.15481	.15660
9	.15838	.16017	.16196	.16376	.16555	.16734	.16914	.17093	.17273	.17453
10	.17633	.17813	.17993	.18173	.18353	.18534	.18714	.18895	.19076	.19257
11	.19438	.19619	.19800	.19982	.20164	.20345	.20527	.20709	.20891	.21073
12	.21256	.21438	.21621	.21803	.21986	.22169	.22353	.22536	.22719	.22903
13	.23087	.23271	.23455	.23639	.23823	.24008	.24192	.24377	.24562	.24747
14	.24933	.25118	.25304	.25490	.25676	.25862	.26048	.26234	.26421	.26608
15	.26795	.26982	.27169	.27357	.27545	.27732	.27920	.28109	.28297	.28486
16	.28675	.28863	.29053	.29242	.29432	.29621	.29811	.30001	.30192	.30382
17	.30573	.30764	.30955	.31146	.31338	.31530	.31722	.31914	.32106	.32299
18	.32492	.32685	.32878	.33072	.33266	.33459	.33654	.33848	.34043	.34238
19	.34433	.34628	.34824	.35019	.35216	.35412	.35608	.35805	.36002	.36199
20	.36397	.36595	.36793	.36991	.37190	.37388	.37587	.37787	.37986	.38186
21	.38386	.38587	.38787	.38988	.39189	.39391	.39593	.39795	.39997	.40200
22	.40403	.40606	.40809	.41013	.41217	.41421	.41626	.41831	.42036	.42242
23	.42447	.42654	.42860	.43067	.43274	.43481	.43689	.43897	.44105	.44314
24	.44523	.44732	.44942	.45152	.45362	.45573	.45784	.45995	.46206	.46418
25	.46631	.46843	.47056	.47270	.47483	.47697	.47912	.48127	.48342	.48557
26	.48773	.48989	.49206	.49423	.49640	.49858	.50076	.50295	.50514	.50733
27	.50953	.51173	.51393	.51614	.51835	.52057	.52279	.52501	.52724	.52947
28	.53171	.53395	.53620	.53844	.54070	.54296	.54522	.54748	.54975	.55203
29	.55431	.55659	.55888	.56117	.56347	.56577	.56808	.57039	.57271	.57502
30	.57735	.57968	.58201	.58435	.58670	.58904	.59140	.59376	.59612	.59849
31	.60086	.60324	.60562	.60801	.61040	.61280	.61520	.61761	.62003	.62245
32	.62487	.62730	.62973	.63217	.63462	.63707	.63953	.64199	.64446	.64693
33	.64941	.65189	.65438	.65688	.65938	.66189	.66440	.66692	.66944	.67197
34	.67451	.67705	.67960	.68215	.68471	.68728	.68985	.69243	.69502	.69761
35	.70021	.70281	.70542	.70804	.71066	.71329	.71593	.71857	.72122	.72388
36	.72654	.72921	.73189	.73457	.73726	.73996	.74267	.74538	.74810	.75082
37	.75355	.75629	.75904	.76180	.76456	.76733	.77010	.77289	.77568	.77848
38	.78129	.78410	.78692	.78975	.79259	.79544	.79829	.80115	.80402	.80690
39	.80978	.81268	.81558	.81849	.82141	.82434	.82727	.83022	.83317	.83613
40	.83910	.84208	.84507	.84806	.85107	.85408	.85710	.86014	.86318	.86623
41	.86929	.87236	.87543	.87852	.88162	.88473	.88784	.89097	.89410	.89725
42	.90040	.90357	.90674	.90993	.91313	.91633	.91955	.92277	.92601	.92926
43	.93252	.93578	.93906	.94235	.94565	.94896	.95229	.95562	.95897	.96232
44	.96569	.96907	.97246	.97586	.97927	.98270	.98613	.98958	.99304	.99651

NATURAL TANGENTS—*continued.*

(In most cases it is sufficiently accurate to use the values to four figures.)

Angle.	.0 =.0′.	.1 =6′.	.2 =12′.	.3 =18′.	.4 =24′.	.5 =30′.	.6 =36′.	.7 =42′.	.8 =48′.	.9 =54′.
45°	1.0000	1.0035	1.0070	1.0105	1.0141	1.0176	1.0212	1.0247	1.0283	1.0319
46	1.0355	1.0391	1.0428	1.0464	1.0501	1.0538	1.0575	1.0612	1.0649	1.0686
47	1.0724	1.0761	1.0799	1.0837	1.0875	1.0913	1.0951	1.0990	1.1028	1.1067
48	1.1106	1.1145	1.1184	1.1224	1.1263	1.1303	1.1343	1.1383	1.1423	1.1463
49	1.1504	1.1544	1.1585	1.1626	1.1667	1.1708	1.1750	1.1792	1.1833	1.1875
50	1.1918	1.1960	1.2002	1.2045	1.2088	1.2131	1.2174	1.2218	1.2261	1.2305
51	1.2349	1.2393	1.2437	1.2482	1.2527	1.2572	1.2617	1.2662	1.2708	1.2753
52	1.2799	1.2846	1.2892	1.2938	1.2985	1.3032	1.3079	1.3127	1.3174	1.3222
53	1.3270	1.3319	1.3367	1.3416	1.3465	1.3514	1.3564	1.3613	1.3663	1.3713
54	1.3764	1.3814	1.3865	1.3916	1.3968	1.4019	1.4071	1.4123	1.4176	1.4229
55	1.4281	1.4335	1.4388	1.4442	1.4496	1.4550	1.4605	1.4659	1.4715	1.4770
56	1.4826	1.4882	1.4938	1.4994	1.5051	1.5108	1.5166	1.5223	1.5282	1.5340
57	1.5399	1.5458	1.5517	1.5577	1.5637	1.5697	1.5757	1.5818	1.5880	1.5941
58	1.6003	1.6066	1.6128	1.6191	1.6255	1.6318	1.6383	1.6447	1.6512	1.6577
59	1.6643	1.6709	1.6775	1.6842	1.6909	1.6977	1.7045	1.7113	1.7182	1.7251
60	1.7320	1.7390	1.7461	1.7532	1.7603	1.7675	1.7747	1.7820	1.7893	1.7966
61	1.8040	1.8115	1.8190	1.8265	1.8341	1.8418	1.8495	1.8572	1.8650	1.8728
62	1.8807	1.8887	1.8967	1.9047	1.9128	1.9210	1.9292	1.9375	1.9458	1.9542
63	1.9626	1.9711	1.9797	1.9883	1.9969	2.0057	2.0145	2.0233	2.0323	2.0412
64	2.0503	2.0594	2.0686	2.0778	2.0872	2.0965	2.1060	2.1155	2.1251	2.1348
65	2.1445	2.1543	2.1642	2.1742	2.1842	2.1943	2.2045	2.2147	2.2251	2.2355
66	2.2460	2.2566	2.2673	2.2781	2.2889	2.2998	2.3109	2.3220	2.3332	2.3445
67	2.3558	2.3673	2.3789	2.3906	2.4023	2.4142	2.4262	2.4382	2.4504	2.4627
68	2.4751	2.4876	2.5002	2.5129	2.5257	2.5386	2.5517	2.5649	2.5781	2.5916
69	2.6051	2.6187	2.6325	2.6464	2.6605	2.6746	2.6889	2.7033	2.7179	2.7326
70	2.7475	2.7625	2.7776	2.7929	2.8083	2.8239	2.8396	2.8555	2.8716	2.8878
71	2.9042	2.9208	2.9375	2.9544	2.9714	2.9887	3.0061	3.0237	3.0415	3.0595
72	3.0777	3.0961	3.1146	3.1334	3.1524	3.1716	3.1910	3.2106	3.2305	3.2506
73	3.2709	3.2914	3.3122	3.3332	3.3544	3.3759	3.3977	3.4197	3.4420	3.4646
74	2.4874	3.5105	3.5339	3.5576	3.5816	3.6059	3.6305	3.6554	3.6806	3.7062
75	3.7321	3.7583	3.[illegible]848	3.8118	3.8391	3.8667	3.8947	3.9232	3.9520	3.9812
76	4.0108	4.0408	4.0713	4.1022	4.1335	4.1653	4.1976	4.2303	4.2635	4.2972
77	4.3315	4.3662	4.4015	4.4373	4.4737	4.5107	4.5483	4.5864	4.6252	4.6646
78	4.7046	4.7453	4.7867	4.8288	4.8716	4.9152	4.9594	5.0045	5.0504	5.0970
79	5.1446	5.1929	5.2422	5.2924	5.3435	5.3955	5.4486	5.5026	5.5578	5.6140
80	5.6713	5.7297	5.7894	5.8502	5.9124	5.9758	6.0405	6.1066	6.1742	6.2432
81	6.3138	6.3859	6.4596	6.5350	6.6122	6.6912	6.7720	6.8548	6.9395	7.0264
82	[illegible]154	7.2066	7.3002	7.3962	7.4947	7.5958	7.6996	7.8062	7.9158	8.0285
83	8.1443	8.2636	8.3863	8.5126	8.6427	8.7769	8.9152	9.0579	9.2052	9.3572
84	9.5144	9.6768	9.8448	10.019	10.199	10.385	10.579	10.780	10.988	11.205
85	11.430	11.664	11.909	12.163	12.429	12.706	12.996	13.300	13.617	13.951
86	14.301	14.669	15.056	15.464	15.895	16.350	16.832	17.343	17.886	18.464
87	19.081	19.740	20.446	21.205	22.022	22.904	23.859	24.898	26.031	27.271
88	28.636	30.145	31.821	33.694	35.801	38.188	40.917	44.066	47.740	52.081
89	57.290	63.657	71.615	81.847	95.489	114.59	143.24	190.98	286.48	572.96

ANSWERS TO NUMERICAL EXAMPLES

CHAP. 3.—**1.** A : B : : 4 : 1.

,, 8.—**2.** 64 : 81 : 36.

,, 9.—**1.** 0.36. **2.** 1 : 1.347. **3.** 10.48. **4.** 64 : 125.

,, 17.—**1.** 8 : 17. **2.** 30°. **3.** 1 : 1.73.

,, 18.—**1.** 3.9 amps. **3.** 2.38 amps.

,, 19.—**3.** 1.78 : 1. **4.** 1.20 ohms. **5.** 600 metres.
6. 264.6 cms. **7.** 3.46 : 1.

,, 20.—**1.** $\frac{1}{3}$ amp. $1\frac{1}{3}$ volt. **2.** 1.5 volt. **3.** 0.25 volt.
4. 30°. **5.** $\frac{1}{7}$ ohm.

,, 21.—**2.** 0.00111. **3.** 0.6654 gram. 351.36 cc.
4. 3387.5 amps.

,, 22.—**2.** 0.197. **3.** 1.67 amp. **4.** 1.63 amp. ; 1.944.

,, 23.—**1.** 2 amps. 4 lamps. **5.** 2 : 3.

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